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HOW DIFFERENCES IN INTERACTIONS AFFECT LEARNING AND DEVELOPMENT OF DESIGN EXPERTISE IN THE CONTEXT OF BIOMEDICAL ENGINEERING DESIGN

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by

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Dissertation

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Dedication

In memory of my father.

For those who made it tough,
for those who made it interesting, and
for those who loved maverick-y me.

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I posted progress on facebook. Just as others show off baby pictures, I posted early dissertation ideas in all their awkwardness.

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HOW DIFFERENCES IN INTERACTIONS AFFECT LEARNING AND DEVELOPMENT OF DESIGN EXPERTISE IN THE CONTEXT OF BIOMEDICAL ENGINEERING DESIGN

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Authentic design commonly involves teams of designers collaborating on ill-structured problems over extended time periods. Nonetheless, design has been studied extensively in sequestered settings, limiting our understanding of design as process and especially of learning design process. This study addresses potential shortcomings of such studies by examining in-situ student team design. The participants of this study are three cohorts of a year-long capstone biomedical engineering design class at The University of Texas. Pilot research demonstrated advantages of a more authentic redesign task over a kit-based design task; students who chose devices to redesign were significantly better at representing perspective taking associated with customers' needs. Pilot research showed that there was no relationship between Early Efficiency (appropriate use of factual and conceptual knowledge) and Final Innovation of design products.

I triangulated various methods for studying design: Qualitative research, Hierarchical Linear Modeling, and Social Network Analysis, the latter of which allowed me to generate team-level statistics of interaction (Cohesion), once I devised a practical method to account for missing data in a weighted network. Final Efficiency is a function of Early Innovation, early and late Cohesion, and team feasibility (factual and practical

knowledge). Final Innovation is a function of Early Innovation, late Cohesion, and team Voice of the Customer (perspective-taking), with all relationships in both models positive. Measures of both design skills and interaction are required to explain variance in these outcomes.

Narratives of team negotiation of design impasses –seemingly insurmountable barriers-- provide deeper understanding of relationships between design process and products. The case study teams spent a large percentage of their time engaged in problem scoping, but framed as engineering science rather than as engineering design. Only when they began prototyping did they transition towards being solution focused and frame the problem as engineering design. This left little time for iteration of the final design. Variance in timing of iteration may account for slight deviations of the case study teams from the statistical model.

Recommendations include earlier opportunities to design and support for team collaboration. Social network analysis is recommended when learning is interactional and to support triangulation.

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CHAPTER ONE: INTRODUCTION

Rationale

Design is a complex activity, yet a common one (Nelson & Stolterman, 2003). It may be considered to be a type of problem solving and is used across domains for various purposes. Scientists design studies and experiments, educators design curriculum, architects design buildings, couturiers design clothing, engineers design devices. Such design tends to be deliberate and in the service of another person or persons, though, as humans, we all engage in altering our surroundings to fit our needs and desires. Such design may be informal and emergent, or governed by rules that may or may not actually hinder design outcomes.

Designers generally collaborate with others as they design. For instance, scientists discuss possible studies within research groups; design of curriculum may involve teachers, content experts, and technologists and engineers design in teams. Even informally, we commonly seek assistance when designing, as when we turn to the internet to get ideas for a vacation, pricing out alternatives, reading others' reviews, and seeking advice of those who have traveled. By relying on a network of more knowledgeable others, we may appear, as individuals, to function at a higher level.

Characterizations of formal design have lead to systematic models of design, and research contrasting novice and expert design provides a great deal of support for these models. Understanding the impact of disciplinary aspects of design adds complexity to this issue. These models are used to frame design instruction, such as for senior biomedical engineering students taking a capstone design course as part of their degree, yet they may not authentically represent the complexity in design processes, particularly for those learning to design.

University-level engineering education programs have tended to reserve design for a capstone experience, in which students are asked to apply the factual and conceptual knowledge and skills gained in engineering science courses as they learn to design. This model has been questioned by some: “Analysis deepens perspective. Design widens it. Both are essential to engineering, but the former has been over-stressed” (Moriarty, 1994, p. 135) and there are advocates for including design throughout the engineering curriculum (Denning, 1992; Denton, 1998; Dym, 1999), as a backbone rather than a capstone (Dym, 1999).

Design experiences in particular may provide students with opportunities to learn about optimization, tolerance for ambiguity, and problem finding. Furthermore, in the context of preparing students for an increasingly technologically demanding world, an undergraduate engineering degree could be considered relevant even as part of a liberal arts program (Dym, 1999). This notion highlights the perspective that the discipline of engineering has relevance for those who will become engineers but also for those who pursue other fields. Extending this perspective to K-12 settings, in which there have been increasing interest and efforts to incorporate engineering experiences, we must consider which aspects of the discipline and of university practice we want to reflect in K-12 settings. If our goal is to provide students with an education rich in problem-solving, collaboration and negotiation experience, tolerance for ambiguity, an understanding of systems thinking, and technological fluency while learning content and skills (Partnership for 21st Century Skills, 2002), engineering design rather than engineering science is promising (Petrosino, Svihla, & Brophy, 2008).

However, modeling this upon current understanding of engineering design is challenging. Despite the ubiquity of design in real world experiences, studies have focused on brief, sequestered design problems in formal disciplines. Our understanding of design has emerged from these studies, leading to an understanding that does not incorporate the role of collaboration. Although engineering design is often taught as a team experience, it is not clear how to support design learning that is collaborative, especially given that models of design process primarily synthesize individual, sequestered design. An understanding of how students learn within teams, considered alongside their designs, would allow for interrogation of models of design process and could foster our understanding of how to support team learning.

Purpose of the Study

The purpose of this study is to investigate how student teams learn to design. Novice designers may rely on informal strategies, or may apply formal rules that are (ir)relevant to their design. Specifically, the differing interactions are elucidated and related to final designs to highlight paths to innovative and efficient team design. In addition, the case study teams afford the opportunity to explore relationships between design process and product, normally assumed to be tightly coupled in statistical models.

For the design of this dissertation study, I employed many of the same tools used by the teams I study (Appendix A).

Research Questions

Of primary interest is understanding what leads design teams to create designs that are innovative and efficient. Implicit in this is understanding what leads to efficient and innovative design learning. My research contributes to understanding the complexity of design process learning by examining in-situ design teams as they interact and learn to design. This research encompasses a pilot study and the main dissertation study.

The pilot study focused on examining whether the design class provided a setting that supported students in developing towards producing innovative and efficient designs, and furthermore, how students in teams learn to design:

- What design activities support students in learning how to design?
- What is the relationship between how Innovative and Efficient team designs are judged to be by experts and measures of design skills and perceptions of learning opportunities?

- How do students leverage resources and mentors and interact as a team as they learn to design?

Results from pilot study questions led to further research questions (Svihla, Petrosino, & Diller, 2007, 2008; Svihla, Petrosino, Martin, & Diller, 2008; Svihla, Petrosino, Rayne, & Diller, 2007). Pilot research indicated that teams interact very differently, both in terms of how they divided tasks and in how they interact with mentors in seeking to learn. Many individuals are part of the system that results in a team's design, including the teaching assistant, faculty advisor, class professors, sponsor, and in a few cases, even the researcher. This aspect was not captured nor represented in the pilot research.

The research questions for the main dissertation study also focused on examining whether and how the design class provided a setting that supported students in developing towards producing innovative and efficient designs, and furthermore, how students in teams learn to design.

A goal within professional engineering practice is to produce innovative design solutions, however, it is not entirely clear yet how to teach for innovation. Students need opportunities to learn Efficiency as well, and to gain experience with the cognitive and affective aspects of design. Pilot qualitative research demonstrated diversity in how students interacted with their mentors; by incorporating measures related to mentors and team interactions, a clearer understanding of how to support such student learning will be possible.

Statistical models provide a sense of trends, but researchers tend to assume that process and product are necessarily tightly coupled. Design process is heterogeneous and complex, and poorly understood in terms of student learning, making this assumption somewhat tentative. Because of the authenticity and complexity of this context, with teams designing different devices, I focused on a meta-level aspect: how teams negotiate design impasses (impasses with be defined and contextualized further in Chapter 6). Particular research questions about case study teams were emergent:

- How can I quantify interaction within design teams and their mentors?
- What is the relationship between how Innovative and Efficient team designs are judged to be by experts and measures of design skills, perceptions of learning opportunities, perceptions of mentors and team mates, and team cohesion?
- How might I characterize novice design problem scoping and the transition towards being solution focused?
- How might students in teams interact and leverage resources and mentors and as they learn to design products, and how does this reflect, contradict, or extend statistical models of whole class trends?

Mixed Methods: Exploring Process/Product Connections

Design process extends across individuals and over months with the problem and solution coevolving during the process (Dorst & Cross, 2001). Such a complex phenomenon naturally has aspects that lend themselves to quantification and others to observation. Mixed methods research allows the researcher to surround the phenomenon. I employed hierarchical linear modeling to quantify relationships related to design products, but incorporated an aspect of design process – measures of interaction. These same measures of interaction, generated through social network analysis, also form the basis for hybrid qualitative/qualitative graphs representing case study teams over time, and evolved in conversation with qualitative analysis of teams negotiating an impasse. These graphs then served as a means to explore connections between design process and product, an assumed relationship in most statistical analysis. In this case, I examined efficient and innovative aspects of design process that teams employed and question whether these necessarily relate to efficient and/or innovative design products.

Significance of the study

This research lies at the nexus of two research communities: the design research community, which encompasses many disciplines but has largely focused on sequestered tasks, and the learning sciences community, which is an interdisciplinary community focusing on learning, with a tendency to invoke more emphasis on the role of technology in learning, though as perspectives have broadened to life-wide learning, this is less the case. Additionally, this research speaks to research on the integration of qualitative and quantitative research, and to engineering education.

This study seeks to refine our understanding of engineering design as a collaborative process that occurs over months, not minutes. Design occurs across individuals in design teams, and with the aid of tools and representations. As design is generally conducted with a goal of producing an object in the world (though other, less tangible designs, such as protocols, studies, and organizations may also occur), it is important to consider the tools that facilitate the design, as well as the nascent design artifacts. During the design process, the design is dynamic, existing in flimsy transient multi-forms. The design changes not only across individuals, but also across time. Understanding how teams interact and relating this to design outcomes will provide a deeper look at collaboration in the context of an ill-structured domain and over extended time periods.

Additionally, this study utilized Social Network Analysis as a bridge between quantitative aspects (HLM), and qualitative aspects by providing both representations that preserve the complexity of interactions as well as mathematical summaries of the interactions. This is a strong link often missing in mixed methods research.

As the study is in the context of biomedical engineering design in a university capstone course, it has greatest significance for this same setting. As this research is not experimental, and does not draw from a random sample but rather from in-situ participants learning a practice, it instead provides a model of learning, exploratory uses of methods, and directions for further research. This study has the potential to inform how design is taught, and may provide support for *when* design might be taught as well, by highlighting the complexity and affordances of learning to design. Findings may have relevance to other areas of engineering, and may suggest the need for similar work in other disciplines. Also of potential significance beyond engineering is the investigation of how and when students seek resources and how teams subdivide challenging problems, and what this means in terms of outcomes.

Design is also considered as having potential for helping K-12 students deal with complexity and ambiguity, and as a way to learn science and math (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kolodner, et al., 2003; Mehalik, Doppelt, & Schunn, 2006, p. 7; Penner, Lehrer, & Schauble, 1998; Sadler, Coyle, & Schwartz, 2000). Although this study does not directly address K-12 design, it highlights potential research opportunities for when design is to be brought into K-12 classrooms.

Delimitations of the Study

Though many possible framings exist and questions emerge when qualitative and quantitative data are collected within in-situ settings over extended periods, it is important to narrow the scope of the focus. Biomedical engineering is a young field, with senior researchers trained in other disciplines. How do those trained in other fields come to this understanding and how uniform are their views of this interdisciplinary field? As these students define themselves as biomedical engineers, they also jointly define the community of practice (Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991).

Observations of students have led me to wonder how this formal practice intersects with their informal experiences: how might courses and the discipline affect life choices the students make and how might learning principled design impact ubiquitous informal design?

Furthermore, observations of teams comprising one woman and three men have raised some cause for concern. Though biomedical engineering tends to attract women in greater numbers than other areas of engineering, a number of instances in which the individual women compromised their strong convictions regarding design directions were noted, or in which they relied upon mentors to validate these convictions. These observations raise questions about how women negotiate their roles within this domain and how they persevere.

These interesting questions lie beyond the scope of this study, though such data are included to situate and contextualize findings, as the discipline intersects with and limits the findings. These questions are yet included as areas for future reanalysis.

Limitations of the Study

This study is set in a biomedical engineering design class at a single university. The students are not drawn from a random sample, but rather from an intact, in-situ cohort of students. This poses serious limitations in terms of generalizability. The generalizability to other disciplines, even within engineering, must be made with care, and the generalizability to other populations must be considered tenuous.

Organization of the Dissertation

In the following chapters, I review relevant literature, and discuss my methods, findings, and implications for this work. Chapter Two comprises a review of research on design and two aspects of my conceptual framework: design process and collaboration. Chapter Three describes pilot research I conducted, detailing initial findings that led me to apply greater emphasis on the social nature of learning, and therefore to include additional methods, detailed in Chapter Four. By combining qualitative research with a hierarchical linear model incorporating measures of interaction from social network analysis, I was able to find relationships observed in case studies but missing from the pilot research. These findings are reported in Chapters Five and Six, with the former focusing on the quantitative results and the latter providing narratives of design teams negotiating impasses in design process. Chapter Seven concludes the paper, comprising triangulation and discussion of my findings, as well as implications and future directions. Appendices with instruments are also included.

CHAPTER TWO: BACKGROUND LITERATURE

A Need for Engineers Who Can Innovate

A plea for engineers who can innovate is made in *Rising above the Gathering Storm* (Augustine, 2005) and in Educating the Engineer of 2020, a report for the National Academy of Engineering, needed attributes of engineers of the near future are entailed as follows: engineers need to possess strong analytic skills, practical ingenuity, creativity, communication, business and management skills, professionalism, leadership, high ethical standards, and be lifelong learners (Clough, 2005). Furthermore, they will need "something that cannot be described in a single word. It involves **dynamism, agility, resilience,** and **flexibility**" (p. 56). Understanding how to instill such qualities in our engineering students, particularly with regard to the latter characteristic(s), is challenging indeed. Many of these skills are comprised within the construct of adaptive expertise (Hatano & Inagaki, 1986).

Adaptive expertise extends prior 20th century understanding and research on expertise by recognizing the need that 21st century experts be flexible and adapt as situations change (Hatano & Oura, 2003). Adaptive experts possess the ability to efficiently solve routine problems, but are also able to adapt to new situations and seek out new learning opportunities (Bransford, Brown, & Cocking, 2000; Fisher & Peterson, 2001; Hatano & Greeno, 1999). Adaptive expertise has been operationalized as two dimensions: Efficiency and Innovation (Bransford & Schwartz, 1999; Schwartz, Bransford, & Sears, 2005). The former relates to the appropriate application of factual and conceptual knowledge and the latter relates to novel approaches, often as a step away from Efficiency.

These dimensions are expressed elsewhere (though using different terminology). For instance, Brewer and Mendelson (2003) highlight the following attributes: creativity, collaboration, and productivity. As they operationalized creativity and collaboration, they found a strong correlation between the two. This correlation is not surprising given that most of the facets of creativity were identical to the facets of collaboration, but this itself is intriguing, because they began from various physiological and emotional characteristics, assigning these attributes to either higher or lower levels of creativity or collaboration, resulting in similar expected characteristics for both creativity and collaboration. This was not the case for productivity, which is expressed in terms of accuracy, timeliness, and thoroughness (Brewer & Mendelson, 2003).

Whether framed as Innovation and Efficiency, creativity and productivity, or analytical skills and flexibility, there is a clear desire for engineers to learn more than is encompassed by engineering science coursework. Engineering design presents an opportunity for students to learn these in concert. I next detail research and perspectives about design in general and engineering design in particular, then present research on collaboration and learning as a social process.

Engineering Design

Design may be considered to be a type of problem solving (Jonassen, 2000), a set of skills (Koen, 1994), and a highly situated experience (Schön, 1987). Understanding design process is limited by the research undertaken, which has largely focused on sequestered or experimental tasks, not on design in the design studio, and not as a collaborative activity. Rather, focus has primarily been on contrasting novice with intermediate and/or expert designers or on categorizing design skills of experts. In most cases, these studies have occurred in isolation of other people, though resources have been available during tasks (Cross, 2004b). For instance, in a focused collection of articles surrounding a singular design task, individual professional engineers spend two hours designing an attachment for placing a certain bag onto a certain bike frame (Cross, Christiaans, & Dorst, 1996). Dorst (1996) raises the issue of using experimental tasks such as those for the study of design. While the task seems to warrant the generation of a taxonomy of design problems, it is difficult to know if the tasks that have been the focus of study are representative, especially as most have occurred in laboratory settings.

Comparisons between novices and experts reveal critical differences in systematic skills employed, informing an understanding of how expert design differs from novice design. Dorst (2003) synthesizes research on the development of expertise in design to highlight the importance of design experience: “we find that how designers perceive, interpret, structure and solve design problems cannot really be understood without taking their level of design expertise into account.” Design is a difficult process to learn, and how the designer negotiates this may correlate with level of experience and level of skill.

Design as Skills

Design may be considered as a set of skills. Koen (1994) posits a behaviorist account of design, in which he reminds us that design, is, after all, a collection of behaviors such that when “we say that a person is designing something, we should be able to look at the individual and observe him or her actively doing something.” As an example, he discusses the training of a pigeon to play basketball with a ping-pong ball and a miniature hoop:

> "…he does not wait for the pigeon to exhibit the complete behavior of flipping the ball into the basket and then reinforce it. Instead, the final, complex behavior is built up by successive approximations. The reward is first given if the pigeon just approaches the ping-pong ball. Then it is withheld until the pigeon both approaches the ping-pong ball and pecks it. Behavior is built up in this way until the pigeon learns to flip the ping-pong ball into the basket.” (p.197)

With this as a model of how to teach design, or any other complex task requiring the integration of implicit, procedural knowledge and explicit, declarative knowledge we are likely to run into problems! A complex systems view of design is warranted as the design process integrates various skills and types of thinking: analytical and synthetic thinking are paired; planning and building iteratively support each other; detailed understanding must be flexibly interchanged with a holistic view; both the cognitive and affective are brought to bear upon the design (Rogers, 2000); and additionally, languages for summarizing and for expanding are required (Dym, 1999). Therefore, design is a complex system and "in complex systems, the aggregate nature of the system is not predictable from isolated components but occurs through the interaction of multiple components" (Hmelo-Silver & Azevedo, 2006) (p. 53).

In another example of design-as-skills, Nguyen (1998) had experts in industry and academia rate the importance of various skills. Industry and academia members rated problem solving highly, but design skills rather low. It is unclear what is meant by design skills, as design skills should be similar to problem solving skills. There are two problems with asking industry and academia to provide this: the skill set is used in an integrated, complex manner, such that the sum of the parts is greater than the whole. Removing or significantly lowering one skill from the set may render others essentially useless. Additionally, simply asking experts what skills they value may not give an accurate picture of the skills they actually rely upon. Academics, in particular, may be biased by the offerings at their campus. While it may be an appropriate means for determining whether to require study of a foreign language or to include a writing component in the coursework for engineering students, it is insufficient as a means of understanding the skills involved in the practice of engineering design.

In another study of design skills, experts were asked to rank, from a list of activities, those skills that were most and least important in design. The skills were described, such that the experts would know what the researchers intended. The most valued skills employed in design, listed in order of most important to less important, were as follows: Understanding the Problem, Identifying Constraints, Communicating, Seeking Information, Brainstorming, Evaluating, Visualizing and Generating Alternatives. The least important, from the very least important to somewhat more important, were as follows: Decomposing, Abstracting, Building, Synthesizing, and Imagining (Mosborg, et al., 2005). This listing of skills is useful in that it highlights the myriads skills valued by designers, but does not make claims about which should be taught. Rather, the authors use it to demonstrate the openness and diversity of design problems and processes.

Another way to frame the attributes and skills desired of engineers is to consider these skills from a cognitive, neuroanotomical perspective. Goel (2000) provides neuroanotomical evidence from studies with individuals with brain lesions that design skills are dissociable, such that they can be partitioned into declarative and procedural aspects. While it is easy to teach the declarative aspects, which are readily verbalizable, it is difficult to teach the procedural. Further, far less attention is paid to procedural. Declarative aspects are insufficient for good design and this may be a major difference between levels of expertise. Though Goel describes these skills, he yet recognizes that to learn the procedural skills, students need opportunities to engage in realistic and authentic experiences, such as design problem solving.

Design as Problem Solving

Considering design as problem solving is appropriate because design inherently is about solving human problems and this can serve to elucidate the process(es) of design. In an overview of problem solving, Jonassen categorizes problems by providing the dimensions of structuredness, complexity, and domain specificity. Problems that are well-structured, by definition, involve the application of finite concepts and rules in a "predictive and prescriptive" manner, such that the solutions are knowable. Ill-structured problems emerge in life, both in an out of the workplace, and do not fit well within constrained school domains, but rather require the integration of various domains. Ill-structured problems involve incorporating preference or opinion while making judgments about unknown and uncertain elements such that there are multiple solution paths to multiple, unpredictable solutions. Complexity is a function of the number of variables, the amount of interconnectedness between variables, the type of relationships between variables, and the stability of all of these over time. Dynamic problems are more complex than static problems. Domain specificity refers to the degree to which domain specific versus domain general methods may be employed in solving a problem. Domain specific problems are situated and contextualized. While logic and story problems are considered to reside at the well-structured, static end of the spectrum, design problems are ill-structured, dynamic, complex and require the integration of domain specific schemas across domains (Jonassen, 2000).

Another way to consider how design problems differ from other types of problems is to examine how specified the problem is; design problems are underspecified, meaning that the problem to be solved cannot be completely given by the initial problem statement (Harfield, 2007). The problem to be solved evolves with the solution (Dorst & Cross, 2001). As an illustration, consider a situation in which the same design problem is assigned to fifty teams; this results not in "'fifty solutions to the same problem' but, in important respects, 'fifty different solutions to fifty different problems'"(Harfield, 2007, p. 160) The problem to be solved, and the resultant solution, will depend on many issues, such as theory, context, ideology and bias, previous experience and attendant knowledge, preconceptions, and "aesthetic and technical sensibilities, based on prior experiences and preferences and prejudices" (Harfield, 2007, p. 169).

A related issue is the degree to which a problem may be considered "determined." Design problems are underdetermined, meaning that design problems are open in two ways. The design cannot be fully defined by the problem statement as a list of needs, requirements and intentions because these cannot be completely listed (Roozenburg & Eekels, 1995). Additionally, the needs, requirements, and intentions belong to a different conceptual world from the structure, though all are resident in the final design (Meijers, 2000). This underdetermination serves to create a rift between the problem as given and the design solution. Design problems are not completely open, however, as constraints may partly determine a problem. However, parts of the design may also be considered to be undetermined, as they rely upon the preferences and style of the designers (Dorst, 2003).

This characteristic in particular has lead to design problems being labeled “wicked” (Rittel & Webber, 1984). Because of the “wicked” and ill-structured nature of design problems, a tolerance for ambiguity is critical for designers. The complex problem solving involved in design has been cast as an “iterative loop of divergent-convergent thinking” in which success depends on being able to “maintain sight of the big picture by including systems thinking and systems design; handle uncertainty; make decisions; think as part of a team in a social process; and think and communicate in the several languages of design (Dym, Agogino, Eris, Frey, & Leifer, 2005).

Design is therefore not a standard case of problem solving. Goel and Pirolli (1992) introduce a framework for discriminating design and non-design problems, and for considering how design problems differ. The framework consists of the task environment, which includes the external environment in which the problem is solved and the problem space, which is the interaction of the problem solver and the environment, and which contains invariant features. The design problem space includes problem scoping, design phases, incremental and iterative decomposable steps, and individually constructed preferences and endpoints. The designer negotiates the problem space, first through a broadening process of problem scoping and then by a narrowing process of becoming solution focused (Cross, 2004a). Some of the qualities that differentiate design task environments from other science problem solving task environments are problem complexity, constraints, how specified the problem is, and how interconnected the sub-problems are. These qualities situate a problem as belonging to design (Goel & Pirolli, 1992).

Not all researchers ascribe to the portrayal of design as problem solving. For instance, Schön (1983) describes it as a process of reflection-in-action, more art than optimization. The artistry involves knowing when to apply a particular procedure or concept. In this view, each design, rather than classified as an ill-structured problem, is inherently unique.

The design process, rather than a search process, is typified as a "reflective conversation with the situation." This situatedness is missing from some descriptions of design as problem solving, especially early views that arose out of observations of early software design, which was highly constrained (Jonassen, 2000).

Design as Process

It is important to point out at the outset of this section that *models* of design are discussed. Models may include the components (or stages) of a system and the relationships between these components, but, by definition, are simplifications used to understand or represent the complexity (Greca & Moreira, 2000). As such, they are inherently limited in their ability to truly mirror design as practiced. They are approximations of design practice. In a review of design and problem solving methodologies from both college level texts and K-12 texts, Johnsey (1995) fits steps from various models into the following categories of activity: Identifying, Clarifying, Specifying, Researching, Generating, Selecting, Modeling, Planning, Making, Testing, Modifying, Evaluating, and Selling, and finds that although there is a high degree of overlap, presenting only one model may not be sufficient for solving the diversity of design problems that exist. Especially as many of them are not supported by research, he warns that these models “do not reflect reality. For instance, the sequence and duration of skills is by no means as clear and simple as described in the published models.” These models, he continues, are overly “tidy models for human behaviour and so it seems reasonable to display a healthy suspicion of such simplistic models” (Johnsey, 1995). While some researchers see this as sufficient reason to omit them from design learning situations, they are yet ubiquitous (Mawson, 2003) and there is evidence from research involving novice designers to suggest that exposure to a model of the process can facilitate the design process (Atman & Bursic, 1996). Certainly, some models of design are overly simplistic and lead to linear enactments of design, but others invite iteration and better represent the practice of design (Johnsey, 1995).

In a study of depictions of the design process, nineteen professional (expert) level engineers from various disciplines drew diagrams of design. The majority of the diagrams were very linear with arrows indicating cycles of iteration, but a few deviated from this norm, instead representing the design process as a cycle. In textbooks, older models were primarily linear, with arrows indicating iteration, but increasingly, models are depicted as cyclic. Cyclic models emphasize some of the attendant aspects of design that can be lost in the linear depictions: iteration, teamwork, and concurrent engineering (Mosborg, et al., 2005).

Wynn and Clarkson (2005) classify models of design as abstract, procedural, or analytical. Abstract models are meant to reflect the general process, but may not offer sufficient guidance. They tend to consist of steps such as Analysis (Defining the problem and needs), Synthesis (generating alternatives), and Evaluation (comparison of possible solutions with needs). Procedural models are more concrete and are therefore more practical, but are also relevant to fewer tasks. These models tend to consist of many stages and may be tied to a particular domain. They also tend to represent iteration, either as a cycle or spiral or through arrows. Steps tend to include Identification of a need, Analysis of the problem, Problem definition, Conceptual design (feeding back into Analysis), Solution selection, Embodiment of solution (also feeding back into Analysis), Detailed design, and Manufacture.

As an example of a procedural model in a textbook for bioengineering design, King and Fries (2003) list the steps of design as follows: Task initiation, task clarification, solution search, solution evaluation, build/evaluate/test, and sell/use. Another procedural model of design, based on a synthesis of textbook representations, includes the following steps: (1) Problem Definition, (2) Information Gathering, (3) Generation of Alternative Solutions, (4) Analysis/Evaluation, (5) Selection, and (6) Implementation/ Communication (Mosborg, et al., 2005). Analytical models tend to narrow the focus more, and are relevant to the specific design tasks they are modeled upon. In addition to this framework (abstract, procedural or analytical), the models of design may comprise cycles of activity and/or serial stages. Typically, stages are more practical in terms of guiding the process (Wynn & Clarkson, 2005).

Atman and colleagues (1999) provide synthesis of the design process as given by college level text books, encapsulating the process into three stages of design in an abstract model: (1) Problem scoping, which involves identifying the basic needs, defining the problem and gathering information; (2) Developing alternative solutions, which involves generating alternatives for the solution, modeling the dimensions and materials to be used, feasibility analysis of constraints and evaluation of optimal solution; and (3) Project realization, which involves deciding on a final solution, communication of the design to others, and implementation of the final design.

A study of student teams designing over a six hour period of time, (Stempfle & Badke-Schaub, 2002) describes two models of design process that teams may adopt, and explains that when a natural/naive design model fails to allow the team to progress, they tend to adopt the other model, which resembles many of the existing diagrams of design process. This would tend to assume that there is a single process enacted naïvely and that when it fails, that designers recognize it as a failure of their model and know where to look to find a better model that is again a fairly uniform process. Because the models in their study are derived from detailed observation of design problems easily completed within six hours, it is questionable as to how well they could generalize to real design process, particularly given that the observations were of students, not professional designers.

Problem Scoping

Good design is considered to be tied to good problem scoping (Atman, et al., 1999), which involves clarifying/defining the problem and gathering information relevant to the design solution. Design is systematic and designers start from first principles (Cross & Cross, 1998) ("fundamental physical principles" (Cross & Cross, 1996)). Experienced designers may question the data that they are given in a design task (Ahmed, Wallace, &

Blessing, 2003). They tend to take a broad approach that is informed by personal preference, then explore the problem space in a principled manner (Cross, 2002), relying on procedural strategies, whereas novice designers rely on declarative knowledge and a depth-first approach (Ho, 2001). Elsewhere, expert designers are described as also employing a top-down depth first approach but with an early focus on design solutions (Ball, Evans, & Dennis, 1994). Expert designers gather more data than novice designers (Atman, et al., 1999), but perhaps more critical, experienced designers pay better attention to the customer needs, logistics, and constraints in the design task (Bogusch, Turns, & Atman, 2000). Novices tend to spend more time on problem scoping than experts, but to less effect (Atman, et al., 1999).

Representation and drawings are used early in the design process to generate and communicate nascent ideas, to offload cognitive burden, to create a shared conceptual space, and to make functions explicit (Stacey & Lauche, 2004). Drawings are used both to explicate routine ideas and to foster nascent novel ideas, and they tend to progress from conceptual to detail oriented (Akin & Lin, 1996) as designers become focused on their solutions.

Becoming Solution Focused

As was noted earlier, the design problem and solution co-evolve, and multiple possible solutions exist (Harfield, 2007). This presents a challenge to the learning of design. If the design problem is malleable and results in myriad solutions, and those solutions are contingent on the preferences and style of the designer, how is one to determine the correctness of a solution? Solutions may be said to satisfice the conditions, to demonstrate that (near)optimization of conflicting goals has occurred (Ball, et al., 1994), but this still leaves the problem of the subjectivity of design, which is tied also to style, defined as “individual characteristics, marking not only the ways of proceeding in design, but also in other complex situations” (Von Der Weth & Frankenberger, 1995, p.

357). This rather disquieting issues lies at the heart of design, again situating it as a wicked problem:

> As all design students come to learn, simply ticking off the items listed in the brief does not guarantee a pass grade. While it may be convenient to discuss design in terms of problem-solving, design is not simply problem-solving. A range of qualitative issues - intellectual and emotional, formal, spatial and aesthetic - not articulated in the brief, and quite possibly not amenable to such articulation prior to their exemplification, by either presence or absence, in the emerging solution, are central to the success or otherwise of that solution. Unsurprisingly, designerly solutions value the nature of the solution above the mere attainment of a solution. (Harfield, 2007, p. 165)

As the design problem and solution co-evolve, and multiple possible solutions exist, a tolerance for ambiguity and flexibility is needed. Designers populate the design process with dynamic, temporary goals. Strategies for solving problems may be local or global, as ill-structured problems are decomposed into well structured sub-problems (Cross, 2002). This requires frequent cognitive switching, but not necessarily the consideration of *broad* alternatives (Cross, 2004a). Flexible strategies are employed (Atman, et al., 1999) as opposed to trial and error strategies, and this offers clear advantages to expert designers (Ahmed, et al., 2003). Von der Weth and Frankenberger (1995) found that domain general heuristics were not good predictors of successful design.

In a study comparing undergraduate freshmen and seniors as they engaged in designing a playground, it was found that considering alternatives and frequent switching between design steps correlated to higher quality designs, and these behaviors increase with experience. Designers must therefore consider alternative solutions (Atman, et al., 1999), and they commonly accomplish this via analogy; experienced designers have a large repertoire of many more relevant analogies based in previous design experience than novices (Stacey & Lauche, 2004). However, as with any type of expertise, greater knowledge is not the only characteristic that differentiates experts and novices. Design is dependent on assimilation of and correct application of many skills.

Experts in design rely heavily upon ideation techniques, which foster analogical reasoning (Gentner, 2002), and upon prior relevant experiences (Ahmed, et al., 2003; Harfield, 2007). This is essentially case-based reasoning, which involves applying past experiences to understand a current problem (Kolodner, 1993; Schank, 1999; Williams, 1992). With experience, designers become more aware of issues related to the task at hand and can efficiently judge which are most problematic, and they become aware of the reasons for use and processing behind a device. This makes them more attuned to trade-offs and limitations and provides them with the ability to question whether a design is worth pursuing, and to keep their design options open, or even to reframe the problem into a new design task (Ahmed, et al., 2003).

Understanding how expert designers engage in design process is useful, but because much of this research has been undertaken in laboratory settings with one designer, extending our understanding towards supporting design team learning is somewhat tenuous. I therefore explore potential issues with the expertise framing and consider research on collaboration.

Design as a Social, Collaborative Process

Towards Social Models of Expertise and Learning

An obstacle of both expertise and adaptive expertise is their fundamentally individualistic nature. Research on experts and expertise has occurred along two main courses (Chi, 2006): Some studies have focused on field-recognized experts (Nersessian, 1992; Resnik & Hart, 2003; Reynolds, 1992), whereas others have contrasted groups with differing levels of expertise (Atman, et al., 1999; Benner, 1982; T. Hogan, Rabinowitz, &

Craven, 2003; Jones & Read, 2005). A shortcoming of both of these approaches to understanding how expertise *develops* is that both tend to hide the social learning processes that support expertise development. When a story of an expert is held up as an exemplar, much as heroes of Greek mythology are, it is done with the goals of edification, that others may follow them. What tends to be masked in these accounts, even those that reveal years of deliberate practice, are the social interactions that facilitated such levels of practice. We must remember that these mythic creatures- just like the heroes of Greek mythology- are supported by many (e.g., Odysseus without a ship and crew would not have made much of an epic). Rather, experts are embedded in social networks.

Research from diverse methodologies is converging on the fundamentally social nature of learning (Csibra & Gergely, 2005; Kuhl, 2004, 2007; Lave & Wenger, 1991; Vygotsky, 1978). Constructs such as distributed expertise or distributed cognition provide a social perspective on expertise, yet are insufficient for understanding situations in which students are learning through collaborative and distributed processes, discussed next.

Collaborative Learning

Though working in a group or team seems to offer great potential for solving complex problems and for learning (Burleson, Levine, & Samter, 1984; Michaelsen, Watson, & Black, 1989), managing this collaboration can be challenging. Group work can be frustrating (Salomon & Globerson, 1989), however, collaboration offers opportunities for students to negotiate their learning by hearing others' explanations (Coleman, 1998), by explaining a perspective (Webb, Troper, & Fall, 1995) and by comparing it to team mates' perspectives (Phelps & Damon, 1989). Furthermore, collaboration, at least in experimental settings, is likelier to lead to strategies and representations rarely found when working alone (Schwartz, 1995; Shirouzu, Miyake, & Masukawa, 2002). In an experimental study of mechanisms for collaborative learning, co-construction (over other-directed or self-directed explaining) led to more ideas generated (Hausmann, Chi, & Roy, 2004).

A challenge to understanding collaborative learning is that even given similar background knowledge, individuals' learning and experiences in group work can be diverse (Barron, 2000; K. Hogan, Nastasi, & Pressley, 1999). Research has shown there to be differences in group performance even when groups have identical tasks, and that success is tied to higher rates of affirming (K. Hogan, et al., 1999). This latter is replicated in other studies as well. For instance, Barron (2003) found that more successful groups had higher rates of connected proposals than less successful groups, and furthermore, more successful groups had higher rates of acceptance and uptake of correct proposals than less successful groups.

Following on Barron's work Chiu (2008) finds that wrong contributions, correct evaluations of ideas, justifications and politeness increased the chances of having a correct contribution whereas questions, rude disagreements, and agreements tended to decrease the chances of having a correct contribution. The quality of contributions has greater impact early in collaborative process in terms of achieving convergence (Kapur, Voiklis, Kinzer, & Black, 2006).

These studies took place in relatively constrained contexts, in which there was a single correct solution but multiple solution paths. Further research is needed that takes the group as the unit of analysis, exploring how groups co-construct understanding and highlighting interactional differences across groups (Barron, 2003). The properties of productive collaboration described above may be more or less important in the context of extended ill-structured problem solving as occurs in design contexts. It is critical to consider that while teams are used to reduce the burden of work for an individual, the complexity may actually be increased due to the need to create a joint problem space and to negotiate diverse skills and perspectives towards a non-deterministic solution (Cooke, Salas, Cannon-Bowers, & Stout, 2000).

Collaboration in Teams

A team may be considered to be a special case of group work, in which the team identifies as an entity and in which the tasks are interdependent such that both individual and group learning are impacted (Guzzo, 1986). In an effort to operationalize team work specifically, Imbrie and colleagues (2005) identified four latent variables: interdependency, learning, potency and goal-setting. Research following on this has shown that when team effectiveness is operationalized as goal setting, potency (teamness), and interdependency, researcher raters are more accurate than the team members in terms of relating to the fourth dimension: learning. As this finding was for short term team collaborations, it may or may not be true for extended team collaboration (Moore, Diefes-Dux, & Imbrie, 2007).

In one study, team effectiveness was operationalized as relating to learning styles or attitudes and as a proxy, explored through student responses to satisfaction regarding their experiences working in teams (Adams, 2001). While students overwhelmingly reported positive team experiences, they did not have within-team agreement when reporting the team's objective, and no relationship was established on whether student satisfaction with team experiences related to learning or other design outcomes.

Team effectiveness has also been operationalized as enjoying working with others, leadership potential and opportunities for feedback. Unfortunately, the questions used to investigate these assessed multiple constructs concurrently (e.g., has strong leadership potential and should take on more of a leadership role.) and even if these had been disambiguated, the constructs provide only a limited view of what team work consists of. This is particularly problematic with regard to leadership; if all team members desired to be leaders, would this produce an effective team? As this framework has been designed specifically for use with short term group work, and because it has not been related to student learning, it has limited use for understanding the complexity of extended team work (Akins & Barbuto, 2008) as would be expected in the context of design.

The coordination of the skills and knowledge held within a team has been considered across disciplines and times, and has been called various things by various researchers (Klimoski & Mohammed, 1994). For instance, coordination of skills and knowledge in non-design teams has been considered from an organizational management perspective to occur via *shared cognition* (Cannon-Bowers & Salas, 2001), *team mental models* (Klimoski & Mohammed, 1994; Mohammed & Dumville, 2001), or *team knowledge* (Cooke, et al., 2000). Shared cognition is put forth as a means to explicate, predict and improve effective team interactions, though questions are raised: "(1) What is shared? (2) What does `shared' mean? (3) How should `shared' be measured? and (4) What outcomes do we expect shared cognition to affect?" (Cannon-Bowers & Salas, 2001, p. 196).

Shared cognition may be task-specific, task-related, or knowledge of other team members. Cognition is shared when it is overlapping, similar, complementary, or distributed. Significant overlap may be detrimental as it may yield groupthink (Cooke, et al., 2000). Shared cognition is measured by examining member knowledge content and structure (schemas), and comparing across members (Cannon-Bowers & Salas, 2001).

This ambiguity has led some to prefer the term *team knowledge* (Cooke, et al., 2000), considered as a subset of *shared cognition* but also encompassing *team mental models*, which include declarative, procedural, and strategic knowledge, as well as knowledge of members' roles, knowledge, style, and preferences. *Team Knowledge* additionally includes the *team situation model, a* task-relevant dynamic understanding of the problem being solved (Cooke, et al., 2000). The *team mental model* is considered to be stable. It is unclear what this view affords, as certainly not all relevant member knowledge always comes into play; the *team mental model* must surely interact with the *team situation model*, effectively altering both. Cooke suggests measuring the collection of knowledge in individuals and within the specific task, though it is unclear if this includes knowledge that is applied or simply resident. Cooke stresses that the knowledge is a moving target, and the rate of change may vary. Measurement must therefore not be static or unidimensional (Cooke, et al., 2000). This is a particularly salient point for the context of teams learning to design.

Design as a Social Process

Design is inherently a social process (Bucciarelli, 1994, 2002; Newell, 1990; Sonnenwald, 1996). Design learning is jointly constructed (Resnick, 1991). Not only is design about solving human problems, it is a social, collaborative process, though this is not always represented in representations from the design community, specifically, not in text books for teaching about design. In a study of how experts view diagrammatic presentations of the design process as presented in textbooks, researchers found that experts generally did not disagree with the diagrams, but found them insufficient. Missing was a focus on tasks associated with the lens of community (Bransford, et al., 2000): communication and multidisciplinarity (Mosborg, et al., 2005).

The latter may be important even when a design appears to fit neatly into one discipline (Arias, Eden, Fischer, Gorman, & Scharff, 2000), in part to avoid fixation (Purcell & Gero, 1996). Note that this view is instantiated within design disciplines through software that helps designers consider solutions from other disciplines (Altshuller, 1996). Such perspective taking has also been linked to innovation (Boland Jr & Tenkasi, 1995).

Although other designers are one of the most important resources an engineer has during the design process, few studies have considered the design team as a unit of analysis, particularly when considering learning. For instance, one example of research on team design that employed mixed methods focused on the roles taken on by professional designers, based upon how and with whom they communicated (Sonnenwald, 1996) but did not consider how this might occur with those learning to design beyond positing that technology could support prescriptive roles for learners. Such possible implications must considered tentative because of the differing goals; in the professional, expert context, the goal is to design a product, whereas in the student context, the goal is to learn design process, with the design product as evidence of this. Other research on professional authentic team design process has investigated organizational change and technological support for physically distributed designers (Baird, Moore, & Jagodzinski, 2000).

In one of the few studies of in-situ team design, Olson and colleagues (1992) used a priori coding to categorize activity between members during early design process, finding that less than half of the time was spent directly discussing design, with substantial amounts of time spent examining progress and coordinating, the latter of which involves negotiating, clarifying, and explaining.

Studies of team learning in engineering have focused primarily on promoting specific team skills or learning/personality styles. For example, Bossert (1988) provides an overview of various types of groups (such as jigsaw groups) and Smith (1995) provides guidelines for how to use groups, with descriptions of different types of groups and ways to evaluate teams. Publications related to capstone design teamwork are not always research based; sometimes claims are made yet not supported by data or analysis. For instance, Magelby and colleagues (1991) claim that industry sponsored projects offer students more motivating learning experiences, particularly when an industry liaison is involved, but these claims are supported only by a handful of student comments with no explanation as to whether they reflect the comments in general. In some cases, they are simply descriptions of courses (Born, 1992; Dorsey, Qu, Magill, & Dawson, 1992; Dunn-Rankin, Bobrow, Mease, & McCarthy, 1998; Durfee, 1994; Free, Gygi, Todd, Sorensen, & Magleby, 1993), sometimes including course satisfaction surveys (Pascual & Uribe, 2006).

In a fairly comprehensive overview of options for teaching design, Dym and colleagues (2005) provide a review of how teams engage in design thinking, highlighting the relevance of Accreditation Board for Engineering and Technology (ABET) criteria. ABET included criteria that address the social nature of design, in that students are expected to possess the following:

- 3(d) an ability to function on multi-disciplinary teams;
- 3(g) an ability to communicate effectively; and
- 3(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.

These aspects are not commonly addressed in preliminary engineering science coursework, and a capstone course may not be enough for students to learn these critical aspects. For instance, in a survey of students at the completion of their capstone design course, most students complained that poor communication was a problem (Pournaghshband, 1990). Additional commonly reported problems were poor leadership, unwillingness of team members to compromise, and procrastination (Pournaghshband, 1990).

It has been argued that “design education should be refocused on teaching designers to better function in group situations” (Minneman, 1991). One suggested route to this is to allow students to view video tape of design activity, and to reflect upon the ways in which members negotiate roles and avoid conflict (Brereton, Cannon, Mabogunje, & Leifer, 1996). Designers greatly benefit from participating in the argumentation aspects of design and the social process of negotiation (Bucciarelli, 1994).

Multiple studies of a two hour segment of group design have also presented findings related to negotiation and roles, though this was conducted in the context of a sequestered task, and has limited generalizability. Brereton and colleagues (1996), for instance, find that utterances as well as gesture are used in team design to indicate agreement or disagreement. Radcliffe (1996) highlights that member actions during design activity are concurrent, addressing different goals, such that parallel processes informed by personal style and disciplinary knowledge and norms are used simultaneously. Although the team sets for itself a model to follow for the design process, as enacted it is much more iterative and emergent in nature. Goldschmidt (1996) compares an individual and a group design process in a sequestered design task, finding that the summation of the activity for the team reflects the activity of the design process for the individual designer, but not for the individual team members. Within a team, each member assumes a role such that in total, all steps of activity are accomplished, but not by all team members. This provides an avenue for exploring how efficiently teams divide their work. When an individual designs in isolation, he or she must accomplish all stages. While in this case, the profiles are similar and the outcomes are similar, it is important to remember that the design task is a constrained, relatively routine task, not a long-term, multidisciplinary task; a task that better reflected this type of design might highlight other differences between team and individual design. Gunther, Frankenburger, and Auer (1996) caution that this analysis can explore the roles as enacted, but it cannot determine the causes of those roles, leaving questions as to how and why roles form unexplored. In another analysis of the same data, Dwarakanath and Blessing (1996) discuss further limitations: The comparison is between a designer with 20 years experience and a team with member experience ranging from 5 to 8 years (meaning that they had different levels of expertise), and with members from different disciplines. The degree to which this is a valid comparison must be addressed and must limit the generalizability of the findings, but the comparison does offer potential questions for further research: To what extent do experience and discipline impact the relative roles of individuals in teams versus as designers on their own, especially in the context of professional practice? Because each team member has different technical skills and values, the resultant “design is an intersection—not a simple summation-of the participants’ products” (Dym, et al., 2005, p. 107).

Synthesis and Initial Questions

In this review, I have presented common views of design, characterized as emergent, iterative, collaborative, situated, ill-structured problem solving. Although not all researchers agree to the use of “problem solving” as a description of design process, the main critiques are applicable mostly to early characterizations of design as being part of typical problem solving; such emerged as a result of studies of design centering on software design, which involves a highly constrained context (Jonassen, 2000). Characterizations of design as a situation in which the problem and solution evolve together are more in line with the situated conversation posited by Schön (1983). I have also presented literature related to collaborative team learning, as this is the context in which design occurs.

In order to extend our understanding of team design learning, I employ mixed methods research to investigate the following questions:

What design activities support students in learning how to design?

What is the relationship between how Innovative and Efficient team designs are judged to be by experts and measures of design skills and perceptions of learning opportunities?

How do students leverage resources and mentors and interact as a team as they learn to design?

These initial questions were investigated in a pilot study, described next, and then extended into further research questions and analytical techniques.

CHAPTER THREE: PILOT STUDY

Study Participants and Context

The participants of this study are senior bioengineering students enrolled in the capstone, year-long design class at The University of Texas at Austin. The study gained IRB approval and students included in the study gave consent. Cohort One is composed of students from fall 2005 through spring 2006 and Cohort Two is composed of students from fall 2006 through spring 2007. Design teams were composed of three or four students who were selected by the course instructors. The instructors ensured that non-native English speakers were distributed across teams.

The class is taught in two consecutive semesters by two different professors. The four teaching assistants (TAs) played a large role in facilitating the students' learning; the TAs had approximately 100 contact hours with the teams and helped with assessment of students' work. Additionally, teams were mentored by faculty advisors and their sponsors.

Both cohorts completed a preliminary project prior to beginning their sponsored project (Figure 3.1). Cohort One completed the mini-project, in which all teams designed digital stethoscopes with the constraint that they functionally incorporate a specific material. Cohort Two completed a redesign project, in which teams selected biomedical devices, such as nicotine patches, inhalers, and pregnancy tests, and redesigned some aspect of the device.

Fall Semester				Spring Semester	
Cohort 1 N=86	Pre-test	Mini-project	Mid-test	Sponsored project	Post-test
Cohort 2 N=82		Redesign project		Sponsored project	

Figure 3.1. Course format and comparison of preliminary projects

After completion of the preliminary project, the teams were selected by sponsors to design a biomedical device or protocol (Appendix B). The projects came from hospitals, industry, government, and universities, and while they varied in terms of difficulty, all were real-world, complex, and ill-structured. Additionally, the skills and content necessary to complete a design may or may not have been a part of the degree program. For example, projects involving circuits may have been challenging because these students do not have extensive experience with circuits, whereas the same project may have been relatively straightforward for an electrical engineering student. Students were given instruction during lectures and completed activities relevant to their designs and the nature of engineering design. Activities included the following:

- Gantt charts are projected timelines, and are updated throughout the project;
- Voice of the Customer, in which students identified and interviewed several potential customers, including a variety of types of customer, such as a doctor, a nurse, and a patient, then coded the interviews to determine customer needs;
- A mission statement in which the teams write a statement about their goals and how they hope to accomplish them;
- A Functional Model, in which the device is modeled based in inputs and outputs of energy, information, and materials;
- Benchmarking, in which students provide a review of literature and patents relevant to their redesigns ;
- House of Quality (HOQ), in which customer needs and other design aspects are contrasted to determine tradeoffs as part of Quality Function Deployment (Hauser & Clausing, 1988);
- Assembly Instructions, in which the students predict how the device functions, then dissect their device, then provide an exploded diagram showing how it is assembled and how it works;

- Ideation, in which the students choose a methods for coming up with possible solutions to a design problem they are having;
- Estimation results, in which students estimate feasible redesign options;
- Pugh Chart, in which feasible redesign options are contrasted along several outcome dimensions (Pugh, 1999); and
- Oral Presentations, in which the teams present their redesigned device

The students typically do little formal team work prior to the design class. Therefore, the intense and extended teamwork the students experience in this course has the potential to provoke new learning of “soft skills” such as interaction, communication, and team work (Seat & Lord, 1998). The lens of community-centeredness (Bransford, et al., 2000) is important for understanding how the students learn in this course.

Study Questions and Overall Design

In order to examine in-situ team design learning, I have been opportunistic in taking advantage of curricular changes made by the course professors, and have included surveys and measures of design skills. I asked experts in the field to evaluate examples of team design work. Finally, I observed case study teams as they engaged in the design process. Cohort One is contrasted with Cohort Two. The preliminary project for Cohort One involved a “canned” design project in which all teams designed a digital stethoscope. This is a commonly used tactic for schools that do not have the means to include sponsored projects. Contrasting the two implementations allows for exploration of how to support student teams learning to design. Questions are as follows:

- What design activities support students in learning how to design?

- What is the relationship between how Innovative and Efficient team designs are judged to be by experts and measures of design skills and perceptions of learning opportunities?
- How do students leverage resources and mentors and interact as a team as they learn to design?

Although this design is limited in terms of generalizability, this design allows for exploration of specific implementations of design learning, which may afford deeper understanding of how to support design learning.

Measures Related to Design Learning

Data Collection and Instruments

Pre-, mid-, and post-tests (Appendix C) and surveys (Appendix D) were completed at an individual level, providing data on how students design, and what their beliefs are about design and collaboration. Team level data, beyond contextual variables (averages of individual measures) include measures of Efficiency and Innovation.

Design Skills Test

The design pre- and mid-test employed the same challenging question each time, and has been used for all Cohorts. It includes a challenging design question (Appendix C) in which the students are told that they are not expected to be able to complete it, but that I am interested in how they begin designing such a problem. This question is used to examine how student thinking changes with experience in design, and involves designing a device for treating hypothermia in war conditions, given several constraints. The pre-test is given in the first week of class and the mid-test is given following completion of the redesign project. The question was written by a domain expert and is challenging enough that even an expert could not arrive at a solution in the time allotted.

A coding scheme (Appendix E) based on expert performance and expert evaluation of student performance was developed. The codes of particular interest include Feasibility, Diagram, and Voice of the Customer (VOC). Using this coding scheme, twenty percent of the tests were coded for inter-rater reliability (92%). Feasibility reflects mostly factual aspects, Diagram is conceptual, and VOC involves multiple perspective taking as students represent the varied needs of diverse customers or end users (for example, doctor, nurse, field medic, patient). This last facet, VOC, it is employed as an individual level measure to corroborate the use of social network analysis to produce team level scores of cohesion. VOC scores reflect perspective taking, which should relate to team cohesion.

Innovation and Efficiency of Design products

Design Outcomes are ratings of how Innovative and Efficient the final design is viewed by experts. A design may satisfy technical requirements yet not be an innovative solution. Both aspects are important for designers. Relating other variables to the final design outcomes, including expert ratings of team project definitions will highlight key factors for innovative design.

Domain experts provided scores of Innovation and Efficiency for student design products. A design may satisfy technical requirements yet not be an innovative solution. Both aspects are important for designers and valued by the community (Martin, Petrosino, Rivale, & Diller, 2006; Martin, Rayne, Kemp, Hart, & Diller, 2005; Pandy, Petrosino, Austin, & Barr, 2004; Petre, 2004; Petrosino, Svihla, & Kapur, 2006). The Early design products (project definitions) and Final designs were both ranked and sorted along the adaptive expertise dimensions of Efficiency and Innovation (Schwartz, et al., 2005) by the spring course instructor, who is familiar with these constructs (Appendix F). Additionally, reliability on the sorting was established with other experts (89%) and by asking the instructor to re-score the same group a second time (93.5%).

Constructivist Learning Environment Survey

In order to assess whether students perceived opportunities to take an active role in their own learning, the Constructivist Learning Environment Survey (CLES) (Appendix G) was administered (Nix, Ledbetter, & Fraser, 2004). This instrument has been validated through several studies, initially through classroom based studies (Taylor & Fraser, 1991; Taylor, Fraser, & White, 1994)and through large scale studies to validate statistical integrity and robustness (Taylor, Fraser, & Fisher, 1997). The CLES measures perceived personal relevance, shared control, critical voice, and student negotiation, and provides a picture of the practices as they exist in the classroom. Traditionally, the instrument also includes a measure for the Nature of Science, but as this is clearly not applicable and in the absences of a well validated scale for Nature of Engineering, this facet was omitted from the measure. The survey is a 5-point Likert scale (1=Almost Never; 2=Seldom; 3=Sometimes; 4=Often; 5=Almost Always). Six questions cover each category. Students completed the survey individually. This survey allows for comparison of prior coursework ratings given at the start of the course to design class ratings at the end of the design course. Additionally, the facets for the design class may be related to Design Outcomes.

Data Analysis: Hierarchical Linear Modeling

I study in-situ design teams, meaning that there is a hierarchy to the data. The students are nested within design teams. Each team's experience may be assumed to contribute variance and to influence team and student level outcomes because students in teams cannot be considered to be independent from one another. Cross level interactions are to be expected. Without including the upper levels of variance, I would risk increasing the Type 1 error rate for analysis. Not considering the impact that levels contribute to variance also leads to aggregation bias and concerns over the unit of analysis, such that impoverished models and related hypotheses abound. Hierarchical Linear Modeling (HLM) is adept at capturing change (Raudenbush & Bryk, 2002). Prior models struggled with conceptualization due to lack of an explicit model, to issues of measurement, which typically involved fixed point measurements of individual difference rather than of change over time, and to experimental design, which commonly relies on only two time points and is therefore insufficient for modeling growth. HLM is flexible with regard to variance of timing of repeated measures, because the data are nested within people. The number of observations can also vary. This model lends itself to study of effect due to the learning environment or community of practice (Raudenbush & Bryk, 2002). Therefore, an appropriate way to analyze the differences between teams is to use a multi level model.

Results: More and Less Authentic Design Experiences

An authentic design task was used to capture some of the changes in how students design. This particular design problem was considered by experts to be extremely challenging, with one expert skeptical about whether it could actually be designed (though it has since actually been designed for use in the US military). The task was developed by Kenneth Diller, who is an internationally recognized authority on the application of the principles of heat and mass transfer and thermodynamics to the solution of various types of biomedical problems. This design task is used to examine changes resulting from experience in design, and involves designing a device for treating hypothermia in war conditions. The problem includes strict constraints as the device must be useable in battle conditions and be able to withstand being dropped from a helicopter without a parachute. Students are told they will not be able to proceed very far into the design, but rather are asked to demonstrate how they would begin to design the device. This same task was posed to students at three time points across the design course: As a pre-test, given the first week of class; as a mid-test, given after completion of a preliminary project; and as a post test, given at the end of the sponsored project. Students completed this task individually. A coding scheme was developed based on expert performance and modified based on discussion with domain experts and learning scientists. The designs were coded, reliability was established (90% with twenty percent of the tests). The coding scheme includes the following categories: Feasibility (Price, Regulations, and Materials); Voice of the Customer (Patients, Doctors, Practicality); Problem-Setting (Features, Context); and Diagram (Material, Heat, Mechanical, System Boundaries) and presents a restricted range problem as most categories range from zero to three. Most of the categories did not show significant differences over time or across cohorts.

Both Cohorts orient to more of a design focus by the post test, meaning that their designs included more information about construction, increased use of and higher quality schematic views, and more attention to the Voice of the Customer. A typical response on the pretest, for example, addressed the scientific aspects related to the heat-transfer inherent in the problem. A typical response from the posttest was more likely to address concrete issues of design, including insulation, temperature monitoring, or how blood could be warmed without damage. These changes suggest that students attend to Voice of the Customer when they feel authentically engaged in the design.

In order to contrast the cohorts, I apply a two level model focusing on the relationship between the pre and mid test across cohorts, excluding the posttest because there is no significant difference between cohorts at this time point (Figure 3.2).

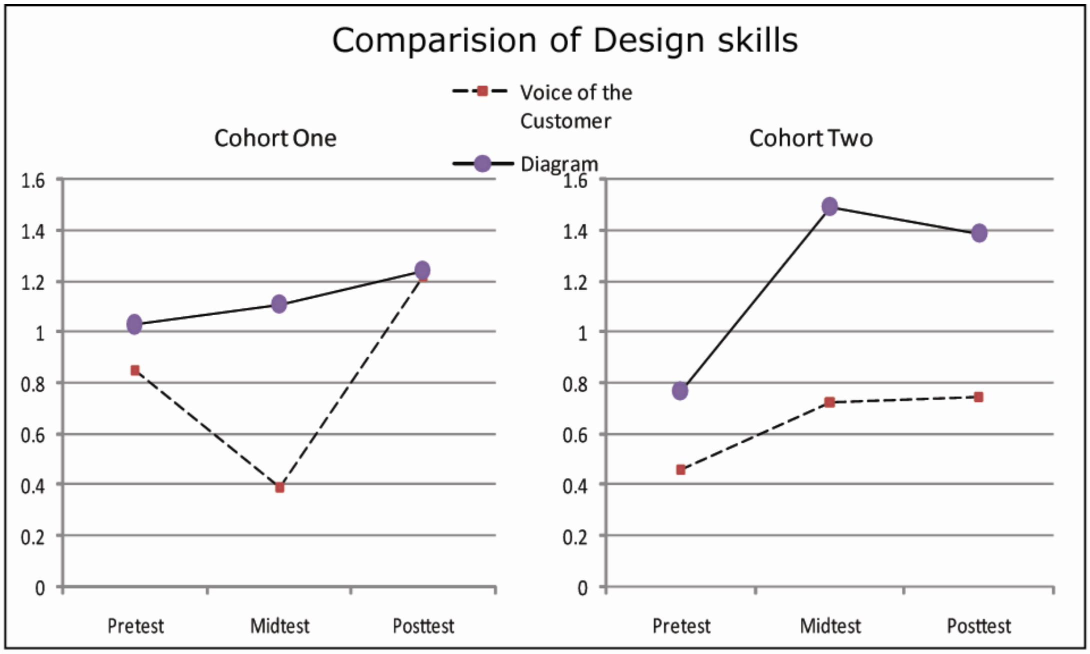

Figure 3.2. averages for Cohort 1 and 2 for Voice of the Customer and Diagram

Beginning with a model that does not include any explanatory variables to determine how variance is partitioned, the student level model includes the midtest scores of Voice of the customer (VOC) as the outcome variable and level two identifies students in teams (Table 3.1).

Student Level Model

$$\text{Mid-test VOC}_{ij} = \beta_{0j} + r_{ij}$$

Team Level Model

$$\beta_{0j} = \gamma_{00} + u_{0j}$$

Table 3.1. Variables in the Unconditional Model

Mid-test VOC_{ij}	Outcome Variable; Score on Design Mid-test for Voice of the Customer for student i in team j
β_{0j}	Average Team Score for team j
γ_{00}	Variance among teams
r_{ij}	Difference between a student's score and the team average
u_{0j}	Difference between a team score and the average team score

The parameters for the unconditional model may be interpreted as follows (Table 3.2): On average, the mid-test score is 0.543. The *t* test result suggests that this is different from zero in the population ($p < 0.05$). The variance of mid-test scores is 0.036. The statistical test result suggests scores do not vary across teams ($X^2 = 52.604$, $p > 0.05$). The residual variance of mid-test scores is 0.459.

Table 3.2. Unconditional Hierarchical Linear Model of Mid-test VOC

Fixed Effect	**Coefficient**	**SE**	***t* Ratio**	**p value**
Intercept, γ_{00}	0.543	0.066	8.219	0.00
Random Effect	**Variance Component**	**df**	**χ^2**	**p value**
Team level, u_{0j}	0.036	43	52.604	0.150
Student level, r_{ij}	0.459			

Despite the fact that there is no significant remaining variance, we can recognize the need to further explore how variance is partitioned based on the very different relationships that can be seen across the cohorts. To further explore how variance in Mid test scores may be partitioned, I include explanatory variables as follows (Table 3.3): Level one includes the pretest scores relating to Voice of the Customer (VOC_Pre) as an explanatory variable for Mid test scores (VOC_Mid) as the outcome variable. Level two identifies students in teams, treating Cohort as an explanatory variable in the Final Conditional Model.

Student Level Model

$$\text{Mid-Test VOC}_{ij} = \beta_{0j} + \beta_{1j}*(\text{Initial VOC}) + r_{ij}$$

Team Level Model

$$\beta_{0j} = \gamma_{00}*(\text{Cohort}) + u_{0j}$$
$$\beta_{1j} = \gamma_{10}*(\text{Cohort}) + u_{1j}$$

Table 3.3. Variables in the Final Conditional Model

Mid-test VOC_{ij}	Outcome Variable; Score on Design Midest for Voice of the Customer for student i in team j
β_{0j}	Average pretest score for team j
β_{1j}	Average relationship between pre and mid test scores for team j
γ_{00}	Average Score for Cohort 1
γ_{10}	Difference between Cohort 1 and 2
r_{ij}	Difference between a student's score and the team average
u_{0j}	Difference between a team score and the average team score

The parameters for the conditional model, which includes cohort both as a main effect and as an interaction term with Pretest, may be interpreted as follows (Table 3.4): Students in Cohort Two score 0.303 points higher on the mid test than students in Cohort One. This difference is statistically significant ($t = 2.155$, $p < 0.05$). Average pre test scores predict mid test scores 0.027 points higher, but this is not significantly different from zero.

Cohort One: VOC_Mid=0.414 + 0.27(VOC_Pre)

Cohort Two: VOC_Mid=0.716 + 0.405(VOC_Pre)

After including team and cohort information in the model, the variance remaining in mid-test score is 0.100. The statistical test result suggests that no variance remains in the population ($X^2 = 36.718$, $p > 0.05$). The residual variance is 0.433.

Table 3.4. Conditional Hierarchical Linear Model of VOC

Fixed Effect	**Coefficient**	**SE**	**t Ratio**	**p value**
Intercept, γ_{00}	0.414	0.098	4.242	0.000
Cohort effect, γ_{01}	0.302	0.140	2.155	0.037
Pre-test effect, γ_{10}	0.027	0.142	0.187	0.853
Cohort effect on Pre-test, γ_{11}	0.135	0.209	0.648	0.520
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.041	27	36.718	0.100
Slope, u_{1j}	0.036	27	29.594	0.332
Student level, r_{ij}	0.433			

These findings suggest that student teams in Cohort Two had significantly different learning experiences during the preliminary project than Cohort One. By allowing students to select devices, and to determine, based on actual customer interviews and needs, what direction the redesign should take, students learned to value the Voice of the Customer. This happens naturally in the more authentic sponsored projects, but did not happen in the confines of the more sequestered stethoscope design task. Although students went through the same basic steps, they did not have a need to incorporate the Voice of the Customer. It is interesting to note that, based on course instructor surveys, student reviews of the two projects also differed, with students much more satisfied with the redesign project (Suggs, 2004, Personal Communication).

Results: Expert Scoring of Designs

In an effort to understand team design, it is critical to have team level measures of design. Sorting, rather than ranking, was preferred because the design projects differed greatly, making it difficult to compare some projects. Additionally, ranking may not have captured the how different two projects were as the scale is not necessarily interval, such that the difference between teams' 3 and 7 designs may be almost imperceptible, whereas the difference between teams' 9 and 20 may be quite large. Sorting allows the experts to leverage their own expertise in developing levels. The design project definitions, completed at the end on the first semester, and the final project designs were sorted according to the adaptive expertise dimensions of Innovation and Efficiency by course instructor and domain expert Dr. Kenneth Diller. In addition to being a domain expert, he has collaborated for 8 years with learning scientists and other domain experts involved in developing research on these constructs (Martin, et al., 2005; Svihla, Rivale, et al., 2007). His position as course instructor and as a researcher with the NSF-funded (NSF #EEC-9876363) Vanderbilt-Northwestern-Texas-Harvard-MIT (VaNTH) Engineering Research Center gives him a unique perspective on understanding and evaluating the students. While I established reliability with other experts, who sorted the designs according to industry standards or on expectations of student design, the mean scores for their sorts would not provide the fidelity of the instructor's scores because the other experts could not incorporate a full picture of the gains many teams made. Because this is a study of students, not of experts, and because students cannot be expected to reach expert levels in one course, only someone who is aware of the students' prior knowledge and experience can deeply assess what was novel for them. As with any other sorting task, greater expertise leads to more complex, deeper categories (Chi, Feltovich, & Glaser, 1981). A sort by someone without this depth of understanding would not capture subtle differences that speak to greater or lesser gains during the design process.

However, I recognize the need to establish the reliability of the scores from the course instructor. To this end, I asked the course instructor to provide scores a second time, approximately 2 months after the course ended. While not identical, the scores were reliable (91% of his rankings on Innovation and 96% on Efficiency). I also had the executive summaries of the final designs and project definitions sorted by three additional experts. These raters never had opportunity to discuss their sorting with each other. Three teams' scores were omitted because these teams provided inadequate executive summaries, such that the experts had insufficient information for scoring these teams. In accordance with common practice, I report a consensus estimate of percentage agreement reliability. Because our scale includes greater than four categories, I include adjacent categories in determining agreement (Stemler, 2004). Rater 1 is a bioengineering faculty member at the same institution as the instructor and has taught the first half of the design course. This rater has greater familiarity with the teams than the other two raters, who teach bioengineering at a private university. These two raters had a high degree of similarity with each other (95% on Innovation, 91% on Efficiency) but a somewhat lower similarity with the instructor. In a discussion of the causes for this, Raters 2 and 3 volunteered two possibilities: First, the executive summaries provided a less complete understanding of the projects, and second, the design projects at this other university tend to be less constrained that the design projects in this study.

The course instructor ratings were examined for correlations. For Cohort One (Table 3.5), Final Design Scores on Efficiency correlate strongly and positively with Final Design Scores on Innovation (r=0.834). This finding suggests that both aspects are part of expert design and can be learned together. Although not quite significant, higher Project Definition Scores on Innovation correlate to higher Final Design Scores on Efficiency, whereas there is no significant relationship between Project Definition Scores on Efficiency and either Final Design Scores.

Table 3.5. Correlations among Scores on Design Products

Cohort One Correlations			Early Design		Final Design	
			Innovation	Efficiency	Innovation	Efficiency
Early Design	Innovation	Pearson Correlation		0.141	0.267	0.397
		Sig. (2-tailed)	-	0.533	0.23	0.067
		N		22	22	22
	Efficiency	Pearson Correlation			-0.028	-0.03
		Sig. (2-tailed)		-	0.9	0.894
		N			22	22
Final Design	Innovation	Pearson Correlation				.834**
		Sig. (2-tailed)			-	0
		N				22

** Correlation is significant at the 0.01 level (2-tailed).

For Cohort Two (Table 3.6), Project Definition Scores on Innovation correlate positively to Final Design Scores on Innovation (r= .665) and Project Definition Scores on Efficiency correlate positively to Final Design Scores on Efficiency. Again, there is no relationship between Project Definition Scores on Efficiency and Final Design Scores on Innovation.

A multiple regression found a significant difference in scores across Cohorts (F (4, 40)=3.173, *p*=.024). Post hocs revealed no significant differences on Project Definition scores of Innovation, Final Design Scores on Innovation, or Final Design Scores on Efficiency, but did find a significant difference across cohorts on Project Definition Score on Efficiency , (*t* = 2.750, *p*= 0.009), with Cohort Two teams scoring significantly higher than Cohort One teams. This difference across cohorts may be interpreted in several ways: As this is the first and second times the course has been taught, the difference may be attributed to improved instruction and design experiences the second time. This is plausible and likely accounts for some of the differences. Another explanation could place variance in the students. However, on many demographic measures, they are identical; there is no significant difference across cohorts on SAT Scores, high school GPA, College GPA, parent's education, or ethnicity. Both Cohorts completed the same prior coursework, and similar numbers of students completed summer internships. Another explanation could be that there are diverse ways of proceeding in design, particularly in novice design, resulting in greater variation than would be expected among experts.

For both cohorts Early Efficiency does not correlate to Final Innovation. This finding is compelling because it runs counter to how we generally teach: develop content and skills before having opportunities to apply them.

Table 3.6 Correlations among Expert Scores on Design Products

Cohort Two Correlations			Early Design		Final Design	
			Innovation	Efficiency	Innovation	Efficiency
Early Design	Innovation	Pearson Correlation	-	0.15	.665**	0.154
		Sig. (2-tailed)		0.495	0.001	0.484
		N		23	23	23
	Efficiency	Pearson Correlation		-	-0.003	.546**
		Sig. (2-tailed)			0.99	0.007
		N			23	23
Final Design	Innovation	Pearson Correlation			-	0.126
		Sig. (2-tailed)				0.567
		N				23

** Correlation is significant at the 0.01 level (2-tailed).

I further relate the expert scorings of the early and final design work to the Pre and Mid test scores on Voice of the Customer. Starting from our conditional model above, I include expert ratings but omit the non-significant Cohort effect (Table 3.7), as follows:

Level-1 Model

Mid-test $VOC_{ij} = \beta_{0j} + \beta_{1j}$*(Initial VOC) + r_{ij}

Level-2 Model

$\beta_{0j} = \gamma_{00} + \gamma_{01}$*(Final Innovation) + γ_{02}*(Final Efficiency) + γ_{03}*(Cohort) + u_{0j}

$\beta_{1j} = \gamma_{10} + \gamma_{11}$*(Early Efficiency) + γ_{12}*(Final Innovation) + γ_{13}*(Final Efficiency) + u_{1j}

Table 3.7. Variables in the Conditional Model

Mid test VOC	Outcome Variable; Score on Design Midest for Voice of the Customer for student i in team j
β_{0j}	Average pretest score for team j
β_{1j}	Average relationship between pre and mid test scores for team j
γ_{00}	Average Score for Cohort 1
γ_{01}	Final Innovation Effect
γ_{02}	Final Efficiency Effect
γ_{03}	Cohort Effect
γ_{10}	Average Slope for Midtest/Pretest for Cohort 1
γ_{11}	Definition (Early) Efficiency Effect on MidTest/Pretest Relationship
γ_{12}	Final Innovation Effect on MidTest/Pretest Relationship
γ_{13}	Final Efficiency Effect on MidTest/Pretest Relationship
r_{ij}	Difference between a student's score and the team average
u_{0j}	Difference between a team score and the average team score

The parameters for this model may be interpreted as follows (Table 3.8): Students in Cohort Two score significantly higher on VOC_Mid ($t = 4.089$, $p < 0.05$), given average Final Innovation and Efficiency. While not statistically significant, it is worth noting that higher scores by Experts on Final Innovation correspond to higher VOC_Mid scores, whereas lower scores by Experts on Final Efficiency correspond to higher scores on VOC_Mid, regardless of Cohort membership. This same trend applies to the difference between the VOC_Pre and VOC_Mid scores. Higher ratings by experts of Early Efficiency corresponds to significantly higher VOC_Mid scores, given average ratings on other parameters, and regardless of Cohort membership ($t = 2.019$, $p < 0.05$). This last finding suggests that the test of design skills captured some of the aspects that experts value as included within biomedical engineering design expertise.

Table 3.8. Conditional Hierarchical Linear Model of Mid-Test VOC

Fixed Effect	Coefficient	SE	t Ratio	p value
Intercept, γ_{00}	0.386	0.094	4.089	0.000
Final Innovation, γ_{01}	0.118	0.067	1.744	0.088
Final Efficiency, γ_{02}	-0.110	0.079	-1.404	0.168
Cohort, γ_{03}	0.360	0.140	2.574	0.014
Pre-Test VOC, γ_{10}	0.055	0.099	0.557	0.580
Early Efficiency, γ_{11}	0.253	0.125	2.019	0.050
Final Innovation, γ_{12}	0.206	0.106	1.946	0.058
Final Efficiency, γ_{13}	-0.164	0.130	-1.255	0.217
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.018	25	31.575	0.171
Slope, u_{1j}	0.002	25	23.025	>0.5
Student level, r_{ij}	0.444			

Further, this establishes that initial scores on such a test of design skills hold little predictive value for recognizing a student's potential as a designer. This, then, has implications that I will discuss later.

I have established that more authentic design experiences lead to better learning. From a constructivist perspective of learning, this would be explained as due to greater opportunities to build on prior personal knowledge in a community or learners. By examining facets of constructivist learning experiences, I may corroborate that authentic design experiences afford such learning opportunities.

Results: Classroom Practices

Meaningful learning is facilitated when students actively construct their own understanding (Windschitl, 2002). Learners are more engaged when they can use their learning to help others (McCombs, 1996). Research has demonstrated that learning is supported when students collaborate on authentic inquiry, (Schwartz, Lin, Brophy, & Bransford, 1999) establishing a community of learners (Lave & Wenger, 1991). Further, having autonomy and a critical voice in how they learn and are assessed fosters student learning (Vye, Schwartz, Bransford, Barron, & Zech, 1998; White & Frederiksen, 1998).

In order to determine whether the design class provided opportunities for students to actively construct their own learning, I asked students to rate their prior coursework and the design course using the Constructivist Learning Environment Survey (CLES), described in the measures section. This survey was administered individually as a post-test for Cohort One and as a pre-test (addressing prior coursework) and post-test for Cohort Two. An exploratory factor analysis indicated that the grouping of the questions was satisfactory for all but one question ("What I learn has nothing to do with life beyond my classroom setting"). Previous research with more general audiences has not reported this effect, but using a restricted sample may lead to different findings. Because this question does not group with the others, it is not considered in the analysis. There were no differences between Cohorts on any dimensions for the CLES when rating the design course.

Table 3.9. Facets of the Constructivist Learning Environment Survey

Category	Sample Question
Personal Relevance	I learned about the world beyond the classroom setting
Critical Voice	It is acceptable for me to question the way I am being taught
Shared Control	I planned what I was going to learn
Student Negotiation	I asked other students to explain their thoughts

While all facets of the CLES showed increases (Figure 3.3), none of them were statistically significant, due in part to low power and in some cases, significant unexplained variance in the relationship between Prior and Design Course scores.

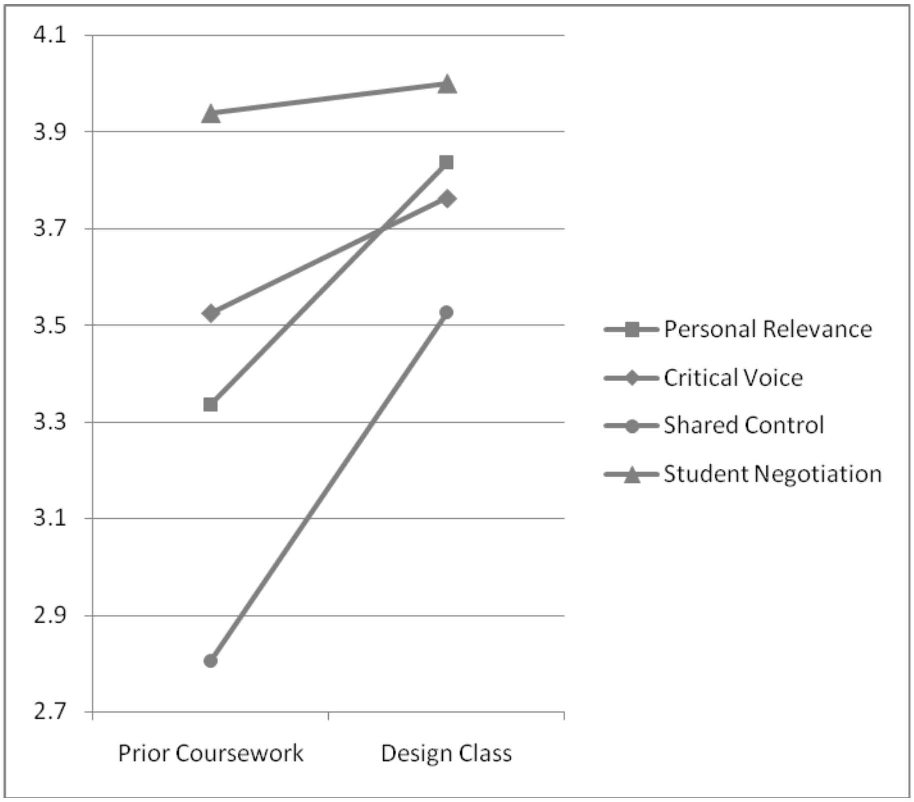

Figure 3.3. Ratings on CLES for Prior Coursework and the Design Class

For instance, changes in Student Negotiation may be somewhat better understood by including Expert Rankings of Final Innovation (Table 3.10).

Level-1 Model

$\text{Student Negotiation, Design}_{ij} = \beta_{0j} + \beta_{1j}\text{*(Prior Student Negotiation)} + r_{ij}$

Level-2 Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

$\beta_{1j} = \gamma_{10} + \gamma_{11}\text{*(Final Innovation)} + u_{1j}$

Table 3.10. Variables in the Conditional Model

Student Negotiation $Design_{ij}$	Outcome Variable; Score for Design Student Negotiation student i in team j
β_{0j}	Average score for team j
β_{1j}	Average relationship between Design and Prior Coursework scores for team j
γ_{00}	Average Score
γ_{10}	Average Slope for Midtest/Pretest for Cohort 1
γ_{11}	Final Innovation Effect on Design/Prior Relationship
r_{ij}	Difference between a student's score and the team average
u_{0j}	Difference between a team score and the average team score

The parameters related to Student Negotiation may be interpreted as follows (Table 3.11): On average, the Student Negotiation score for the Design class was 3.977. The t test result suggests that this score is different from zero (t=28.314, $p < 0.5$). On average, students score the Design class 0.315 points higher than their previous courses. This increase is not significantly different from zero (t = -0.707, p = 0.489). Higher scores by experts on Final Innovation correspond to significantly higher Student Negotiation for the Design class (t=2.395, $p < 0.5$).

The variance of individual scores for the Design Course is 0.000. The statistical test result suggests that scores on Student Negotiation do not differ significantly across students (X^2= 9.723, p => 0.500). The variance of team scores is 0.020, and the statistical test result suggests that scores do not vary significantly (X^2= 12.746, p = >0.5).

Table 3.11. Conditional Hierarchical Linear Model of Student Negotiation

Fixed Effect	Coefficient	SE	*t* Ratio	p value
Intercept, γ_{00}	3.977	0.140	28.314	0.000
Prior Student Negotiation, γ_{10}	-0.315	0.446	-0.707	0.489
Final Innovation, γ_{11}	0.757	0.316	2.395	0.029
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.000	12	9.723	>0.5
Slope, u_{1j}	0.003	11	12.746	0.310
Student level, r_{ij}	0.867			

Essentially, this means that for those students who ranked the design class higher in terms of having opportunities to negotiate, experts tended to score their final designs as more Innovative. This would suggest that the interactions within teams are a critical aspect of producing innovative design, though there remains further unexplained variance in this model.

These findings indicate that the nature of the design course gives the students greater control over their learning than their other coursework tends to, and that by engaging in an authentic design experience, they are afforded, though may not take advantage of, opportunities to negotiate their own learning.

Qualitative Data and Analysis: Observations of Team Design Process

In order to examine the design process employed by a team, one must look beyond the individual team members and consider the interactions with the various mentors. Each design team is assigned a teaching assistant and sponsor, but they must seek out a faculty advisor and many teams seek out additional mentors, either on their own initiative or on the advice of an existing mentor. Teams and individuals within teams interact differently with their various mentors, and I observed that these interactions have direct and indirect impacts on the team's design process. My remaining pilot research question, how do students leverage resources and mentors and interact as a team as they learn to design, was investigated through case study.

I selected three case study teams to follow according to the following criteria: The course instructor provided a list of teams she thought might be interesting to study, and grouped them into high, medium, and lower performing teams, based on early homework exercises. Omitting those teams in which students had not consented to participate in the study, I selected three teams as a stratified random sample. I attended all team meetings to the best of my ability as an individual researcher, taking detailed field notes and audio recording interactions. I annotated my field notes after the meetings, and informally interviewed the students as questions arose or for member checking of my interpretations. Partial transcripts were generated directly after leaving the field, followed by more detailed transcripts.

Because these case studies extend over months rather than hours, and because they are heterogeneous in terms of projects, a microanalytic coding approach to analysis is not appropriate. As my goal was to describe instances of design learning and not to develop theory about design learning, detailed coding is not required (Corbin & Strauss, 2007). Rather I systematically examined transcripts for interactions relating to mentors and resources. These I then pulled into a narrative format including further transcript to provide context.

I provide two contrasting cases from Cohort Two to highlight challenges students faced in their design teams, and to demonstrate the diversity of interactions with mentors. These vignettes from two teams demonstrate diversity in how design work and learning are distributed in design process, and have implications for supporting design teams. Note that in order to protect the intellectual property of these authentic sponsored projects, specific materials and processes are simplified or renamed. Names have also been changed.

Team 2.1

Team 2.1 is a three-member team, with two native English speakers, Jeff, a Caucasian man and Ally, a Caucasian woman) and one native Bengali man, Samresh. This team is designing software to search for materials contained at diverse locations and organizations. The design project is situated as a biomedical design project by virtue of the knowledge needed to organize appropriate search software for the biomedical materials. However, the project requires computer-specific knowledge that Jeff and Samresh gain by taking a course with their faculty advisor, who is a computer scientist. Ally focuses on other aspects of the project, such as economic analysis and learning about the formalities that would be required of participating users. She also explains to us that she must rewrite and heavily edit Jeff and Samresh's work. The teammates rarely talk about their outside activities or lives.

At one of the first meetings I observe, Jeff, who is the only one to show up on time, explains to us that Ally is the one who keeps pushing them to meet, to work together, but that they have their own parts to do. Ally arrives late and sits at a computer far from Jeff, never interacting with him, but later complaining to us that her team mates had not been meeting and that they were leaving things until the last minute. I observe the team during monthly conference calls with their sponsor and never see Ally in attendance.

This team's TA was educated in South Asia until beginning his graduate program in biomedical engineering though he has familiarity with the type of computer software they are designing. He sometimes contradicts the faculty advisor, but the team is not sure whose advice to trust. He occasionally arrives late to team meetings, but seems to understand the project (This is not true of all of the TAs.). When unable to attend one meeting, he emails his team 15 minutes after the start of the meeting to let them know, and they chat about this and their project:

Ally: We haven't had the three of us together since the [first] conference call. [...]
Jeff: [reading email from TA saying he will not be able to make it] "mail me the updates"

Ally: There are no updates. I haven't worked on the audit trail I was supposed to work on this week.
Jeff: [The TA] said IRS form instead of IRB form.
Ally: I don't understand how he can still not know what our project is or anything we've told him.
Jeff: Well, think how many groups he has, probably has like four groups, and he's probably like doing research for a professor.
Ally: And our project proposal was completely off as far as our deliverables go.
Jeff: Oh yeah. It would have been so much better if-
Ally: Did anyone email him with that presentation?
Jeff: Uh-huh. I think so.
Ally: Well that has, that's much better on stating what our deliverables are.
Jeff: No he, uh, … It just would have been so much better if we would have got to meet [our sponsor] before, um, a month ago.
Ally: We really need to meet several times next week to come up with our oral design presentation. [...]
Jeff: Next week Tuesday evening I'll be here for however long it takes. and I mean, we already have a lot of slides done, it's just now we need to go in and change the stuff that we said oh this the stuff we're gonna do to say, this is what we have done.

In a later conference call with the sponsor, Jeff and Samresh discuss a presentation they have sent to the sponsor. All of her concerns, however, relate to Ally's sub-tasks. Ally is not present, and Jeff and Samresh attempt to explain her work to the sponsor:

Sponsor: Why do we think the numbers are correct, what are the assumptions? What's the framework you want to do your cost analysis and revenue analysis? What I have not seen in your powerpoint presentation is a list of assumptions. So like, you built up the model of what you are working on but then you jump into slide six and I am saying, where do these numbers come from? First you tell me what your framework is, before you tell me what the [levels are].
Jeff: Umhmm.
Sponsor: But that's the missing piece right now- assumptions.
Jeff: I believe, um, Ally was in charge of doing these membership slides and I think the, the basis of where she got these numbers from was uh, I mean I don't know, the, one of those first conference calls we had when you defined the deliverables to us, you wanted the user membership and you kind of wanted if we were gonna go the route of having, like, say [different levels of membership] you wanted us to come up with the numbers, uh, where the cutoffs would lie, as far as when it would be

more beneficial to upgrade and get the next higher membership plan. I'm pretty sure that's how she got these numbers. I mean, other than that aspect, when she looked at it, I mean, the numbers are a little bit arbitrary, I believe other than the fact that, they are kind of realistic. I mean if you look at 'em, you would, you could see, I mean a heavy duty researcher that's ordering a lot [...] I mean you could see 'em being on the system for you know, 5 or 8 hours a month. I mean that's realistic I think, but uh…

Sponsor: I agree, I agree, 5-8 hours a month is definitely realistic, but that has to be a slide [explaining it as an assumption]. [...] So, 9.1 hours, is that hours per month. Where are we getting the [number]? [5 seconds of silence] I guess what I need to see is the spreadsheet so I can see the relationship between these numbers.

Jeff: umhmm. I'll uh, I do believe that Ally does have a spreadsheet, I mean, like I said, these, um, are her slides, I mean, uh, there is some logic behind how she chose these values. I don't, I mean, I'll uh, I mean I do remember when we presented this presentation, was the week before spring break, kinda, she was going over the slide. I mean, I was a little bit confused when she was talking about it but she could probably either, uh, maybe either send you an email, uh, with the spreadsheet, uh, and uh maybe a paragraph explanation, kinda how she came about that. Maybe you could give her some feedback that she could maybe look to do different, uh, for the future.

Sponsor: Sure, if you could please follow-up with her and ask her to send all of us the spreadsheet and also in an email tell us where she came up with the numbers in slide six. That's the missing piece right now. I will rely on both of you to follow-up with Ally and get her to send all of us the spread sheet and the assumptions behind slide six.

Though Jeff and Samresh relate this to Ally, it becomes clear during that final presentation that she has not addressed the sponsor's concerns. As Ally explains how customers would be charged (one of the issues the sponsor had concerns about) Jeff rolls his eyes and interrupts. The sponsor again highlights concerns over the scheme, and questions them during their presentation. It becomes clear that Ally never understood what it was the sponsor wanted. Additional problems emerge during discussion:

Sponsor: [We are] focusing on [this type of] software. We sell a package to [organizations and individual clients] and [the] students here are designing a way to connect them.

Faculty Advisor: I didn't completely understand this until today… it is a business to business portal. I have misdirected the students in some ways, I'll contact you.

Ally: I didn't know they were already selling software. The sponsor gives us incomplete information.
Faculty Advisor: There has been a breakdown of communication. They should have been better.

After presenting their final design solution to the course instructor, sponsor, TA and faculty advisor, the team launches into excuses for why they did not do as well as they should have:

Ally: We were a little bit disadvantaged. Just a tiny…
Jeff: Our group was, like, three people- you've seen us [to researcher]. One of our members was never there. She's like, yeah, I know.
Ally: Thankfully though, we had three, I mean, even though I was out of commission for a month or three weeks or whatever, still you know, I think we had three members who worked equally hard and worked cooperatively and I think we worked great as a team. I think that our individual work was great and… I know that I was, that I got more final stuff that I was always late on things, but you know, I , I think that we did, uh, um, that for having three members and everything, we still did pretty good working together.
[Samresh shifts his eyes down and away from her] [...]
Faculty Advisor: The presentation would have sort of benefited from a more sort of a hierarchical
Ally: Yeah, I don't think the organization of the slides is good, is that what you mean?
Faculty Advisor: Well, I mean that's how it manifests, right, it's, I wanna talk about this, and sort of provided it in the most briefest of terms and then you know, then drill down into it, or, I'm gonna talk about A, B, and C, and this is what A's about, in detail.

When rated on Innovation and Efficiency by experts, their Final Design scored among the lowest in the class. One might attribute this to the fact that Ally solved very different sub-tasks than Jeff and Samresh did. However, many design teams are multidisciplinary; therefore, it was not that Ally had different tasks than her teammates that caused problems in this team. Distributing tasks across members is an effective way to solve ill-structured problems. Likewise, one might consider that the team has only three members rather than four to be the cause of their problems. However, the faculty advisor and sponsor felt that the team members worked hard and that simply adding another member would not have made the difference. What, then, caused the struggles portrayed in this vignette? The consistent lack of communication created problems for this team. While they did distribute their tasks, they did not dynamically negotiate the tasks. Because the design problem and solution co-evolve (Harfield, 2007), frequent (re)negotiation of subtasks is a requisite for success. Team members need not be best friends, but they need frequent enough contact to coordinate their efforts and they need to trust each other enough that they are willing to change what they are doing as the task is redefined. The team members did not develop friendly relationships, and this is reflected in the complaints Ally and Jeff made to the researchers about their team mates, and in the responses of Jeff and Samresh to Ally as she speaks.

Team 2.2

Team 2.2 is a four-member team with three native English speakers: Clint, a Caucasian man, Shelly, a Caucasian woman, Lissa, a South Asian American woman, and Andrew, a native Mandarin speaking man. Clint is the team leader in name, though Shelly commonly makes contact and directs the course of their actions. In fact, when it is mentioned late in the semester that Clint is the leader, I am surprised because Shelly acts as team leader in most situations.

The TA for this team, Sanjay, is a young South Asian American man, in his first semester after graduating from the same department and having the previous year been a student in this course. He is enthusiastic with his teams.

Their sponsor, the director of a local biomedical technology company, is one of the few that contributes several projects each year, but he delegates mentorship to specific people within his company. His projects are often innovative or exploratory, and his standards are very high.

The team members spend time talking about outside interests and activities, and keep each other up to date on sub-tasks. Their design task is to identify a biocompatible material that meets specific constraints.

This team's impasse centers around a moment in which their project seems impossible, but when they try to re-scope the project with their sponsor, he requests that they contact their faculty advisor. This is an example of delayed problem scoping; they can't see the problem until they mess about with it; only then do they understand why this is challenging.

At a point approximately three months into the project, the team has hit an impasse; they can see no way forward. The first mention of the impasse occurs Feb 7 as the TA is questioning them about their progress after an interim presentation, though they have clearly discussed the issue amongst themselves previously.

One of the tools design teams employ to help them see options is to consider analogies. The value of these is either to create a shared understanding or to think about how some function is accomplished in another context. Neither seems to be the case in this instance:

Shelly: The difficult part, we can either use salt leaching if they are willing to move away from the pourable injectable or sprayable, or we may have found another type of polyurethane that can be made, uh, injectable.
Andrew: Like the-
Shelly: The problem is we would have to see if that processing could be applied to the new polyurethane […] and still retain all the properties that make it good. […]
Clint: It's basically a two polymer deal so it could be transported separately.
Shelly: Kinda like Drano. [Shelly laughs]
Clint: Yeah then once its mixed you put it, [Shelly continues to laugh, TA looks confused by analogy] then once it's mixed you have time to put it in the site.

This analogy to Drano is not picked up by Shelly's team mates, but Shelly continues to use it. They explain to the TA that they have identified several possible materials, but none of them address the main and most novel aspect of their project, that the material be pourable, injectable, or sprayable such that it forms a foam:

Sanjay: And what's wrong with PCL?
Shelly: Nothing's wrong with PCL-
Clint: I mean-
Shelly: -except it's not injectable pourable or sprayable uh any processing that can be applied to PCL basically needs crosslinking, so you're gonna have to do some kind of gas foaming salt leaching most people use salt leaching.
Andrew: That's um it would be cool to use pcl in addition to like plj or polyurethane.
Shelly: Yes PCL is great.

They continue to explain the properties of PCL that make it desirable, then mention that they'll be meeting with their sponsor that afternoon with hopes of renegotiating the scope of their project. Sanjay goes on to suggest some resources for them, then inquires about the sponsor's expectations.

Sanjay: What was final deliverable for you on this project? […]
Andrew: It wasn't required, he just basically kinda wants a prototype and then data that goes with it.
Sanjay: Preliminary testing results?
Shelly: Really they wanted the research mostly. […]
Lissa: I think [the sponsor] puts a lot of emphasis on research.
Shelly: On the research yeah, I mean I think that their willing to let us do some testing and stuff, it was more of a giving us hands on opportunity. It's not really necessarily gonna to help them a whole lot, […] so basically he told us all wants us to do is see if it's even feasible, he doesn't want us really to do, uh.
Andrew: Very much.
Shelly: He doesn't want us to find something that's going to work tomorrow because they're gonna do years more worth of research before uh they actually start applying something.

Later that same day, they call their sponsor and propose re-scoping their project. He encourages them to seek help first, but lets them know that if his suggestion does not work, they can discuss re-scoping:

Sponsor: You guys talk.

Shelly: AHRIGHT. so I guess our uh main concern today one of our main questions is was we wanted to know what you felt about our design goal uh including the pourable injectable or sprayable uh processing method um we did find one paper on injectable polyurethanes but it extremely recent like it was just published last month- uh or something like that but um that's the only thing we've found that's even remotely close to finding a pourable injectable or sprayable method of delivery for any of these polymers that we've been looking into uh most of the processing techniques require salt leaching or something like that we were wondering if we should try to limit our scope um to not include the pourable injectable or sprayable or what you felt about that.

Sponsor: First, uh, would you be able to forward me a copy of that article.

Shelly/Clint: Yes.

Sponsor: Secondly, have you consulted with [your faculty advisor]? Does she agree with your findings?

Shelly: Um, no we have not consulted with her about this particular thing we wanted to talk to you about it first but we would be willing to go to her, she might even be in her office right now, um.

Sponsor: Yeah, I would try doing that. I would take advantage of that because she also has pretty extensive background on biomaterials.

Shelly: Right.

Shelly: And she you know, you're right, pretty complex, far away, consistent with what I know, might not be much you can do if [inaudible] consistent with what I have encountered now the thing is though with me I am not as current with the academic research that is going on that I am aware of, um so I would not rely too much on what my knowledge would be in terms of that that's why I was hoping that you guys would

Shelly: Right.

Sponsor: Talk to [your faculty advisor] see whether she agrees that's a reasonable assessment based on your literature search.

Shelly: Definitely, we can definitely talk to her about that.

Sponsor: And if you know, if she agrees that you know that we do need to re-scope then I'm okay with that as long as we put the rationale for why we chose to scope that's okay with me.

One week later Shelly and Andrew meet with their faculty advisor, a professor in biomedical engineering. They explain their impasse:

Shelly: There are a lot of materials that we've looked into. But the problem with all of them is the processing methods, are almost invariably, Salt leaching, gas forming. There is no way for them to be quickly processed and cross link to the extent, that you get an open-cell reticulated foam. […] that has the mechanical properties that we are looking for. Without preprocessing it in some way, they didn't like the freeze-drying idea for some reason, they said if we were going to do something like that or we have to preprocess then we would have to look for a completely new material that hasn't been used ever before.
Faculty Advisor: Oh, gosh forget that.
Shelly: Yeah,
Faculty Advisor: You can come up with, you can theorize all you want to. But you won't have anything in your hands-
Shelly: Exactly.
Faculty Advisor: -at the end of the semester.
Shelly: So, [the sponsor] wanted to know if you thought it was possible to still do pourable, injectable or sprayable.
Faculty Advisor: It all depends on your material.
Shelly: Yeah, I know,
Faculty Advisor: That's the thing,
Shelly: Well, what characteristics does the materials have to have first to be able to make it that way, 'cause we haven't found anything that.
Andrew: Like we found like all the polymers for the um cement mixing-
Shelly: Yeah, which are injectable.
Andrew: -and then they don't-
Shelly: But they don't have the mechanical properties.
Faculty Advisor: There are not going to have foam.

Their Faculty Advisor enters into the problem space, rapidly positing and eliminating options, a process described as reflection-in-action (Schön, 1983):

Faculty Advisor: Now the way that some people do make porous systems, is you include salt.
Shelly: Mmhmm.
Andrew: Right.
Faculty Advisor: And then you soak it and the salt all dissolves out.
Shelly: But on person's wound is that really?
Faculty Advisor: That's really bad idea. […]
Andrew: If it was already premade and then you could just like kinda ?
Shelly: Mix them, two, and kind like Drano.

This analogy does not bring laughter this time, but again, no one else picks it up. Finally, the Faculty Advisor begins to come up with a possible solution:

Faculty Advisor: Can you have something? We have polymer and then you have, gelatin. Okay.
Andrew: Okay.
Faculty Advisor: And the polymer will cross link with light.
Shelly: So for polymerization?
Faculty Advisor: For the polymerization. […] Because the gelatin also, if you're pulling something, the gelatin then will come out and will leave you a porous network that is hydrophilic network.
Shelly: That would be very good, actually.
Faculty Advisor: So you need gelatin plus something
Shelly: The problem is how are we going make, well now the photo-polymerizing, you know, we have kind of thought about that [FA: yeah] but we weren't sure if they would want to have an entirely different, 'cause they are going to have an entire photo-polymerizing system in order to do that. You know, like the guns that people put in the mouth for dentists.
Faculty Advisor: Yeah! But-
Shelly: That wouldn't be a problem you don't think?
Faculty Advisor: I don't think that, shouldn't be a problem.

The Faculty Advisor goes on to tell them about a professor who will be visiting who has expertise in this area and who happens to have attended the same school she attended. She goes on to suggests search terms they should use to find more research:

Faculty Advisor: So, do a search on ISI web of knowledge, um, for photopolymer* so, you get photo polymerization, polymerize, all that, um degrade, kind of thing. Do those and see what shows up. So you may get some photo polymerizable, degradable eventually degradable systems.

The Faculty Advisor then reflects again on the feasibility of this new possible solution, carrying out verbal tests of this new idea:

Faculty Advisor: Um but the gelatin shouldn't be a problem, it really shouldn't be a problem..[…] Like, if you have molecular pores as opposed to thicker pores […]

here’s what you do. you make micro particles of gelatin at the size that you want. Keep 'em cold! cause if you get them too warm they’re gonna to turn in jello um then you can mix those with your quickly!, with your water solution of your polymer, spray it and then cure it. The gelatin particles, are not cross linked, they should start then defusing out and leave you those size, holes. Now, I don’t know if the gelatin is going to start coming loose in your system, or what.... you know, you got all those variables. I don’t know if it’s practical to do all this, in cold refrigerator temperature or not. I don’t know. But that, that’s a possibility to make the gelatin particles.

Once she has assured herself that this is feasible to do, she offers a “recipe” for making the particles so that they will have a prototype in hand. This seems to be important for the teams in terms of motivation. When doing a feasibility study, it can be challenging for the students to find and maintain a design focus. The Faculty Advisor continues to explore this possible solution, considering options for freezing the particles. Then she again reflects on the problem space:

Faculty Advisor: But anything else I am thinking, I mean, I just keep going back to gelatin, because it is just such a nice innocuous thing

Andrew asks for clarification, and this brings up a minor complication:

Andrew: And this is in a water polymer solution?
Faculty Advisor: Yeah.
Andrew: And that will not affect?
Faculty Advisor: Because you want…
Andrew: How like the polymer degrading, anything?
Faculty Advisor: Oh, it will-
Andrew: Okay?
Faculty Advisor: -it will. The question is how much, just anything, you want it freeze dried, maybe then you will have to hydrate first, before it starts dissolving, because it will dissolve!
Shelly: Yeah.
Faculty Advisor: But you haven’t crosslinked it. The question is how long would it take to dissolve, what you can do, and if you start out with 500 micron particles and you only want three hundred micron holes.

She continues to explore this solution with Shelly and Andrew.

Andrew: I am just trying to see picture of how to so we're dissolving a little bit of polymer and then putting in the gelatin and then and then is that all?
Faculty Advisor: Yeah, it's like you have a polymer solution.
Andrew: Aha.
Faculty Advisor: So, you got polymer water.
Andrew: Alright.
Faculty Advisor: Then you add the gelatin particles.
Andrew: Aha
Faculty Advisor: Mix it up, spray it on, cure it. so then the gelatin particles, are not crosslinked, so you still have these chains, so they will then diffuse out, because you have a hydrated system right there, and I don't know how hydrated then, it will stay once you because once you want cure it, you're cross linking it, so it's going to be tighter so the water, that it was there, would have to go somewhere, and the micro gelatin particles might come out, you know, all kinds of crazy things it could happen that way. That seems to be a way to make holes.

While this solution now seems very promising, the Faculty Advisor again explores the problem space, asking Shelly what ideas they had considered, and then relates their plan to the current solution:

Shelly: We were trying to find a mechanical way of forming of foam structure with these, because all of these things can make foams.
Faculty Advisor: Yeah.
Shelly: Unfortunately the processing is salt leaching and-
Andrew: And we were-
Faculty Advisor: And salt, yes, that's what I said so, but salt, no-
Shelly: Yeah, and-
Faculty Advisor: No, no, can't do salt.
Shelly: It's not, not-
Andrew: And we were hoping there was some way we can like apply.
Faculty Advisor: Yeah, but essentially what you are doing is gelatin leaching.
Shelly: Yeah basically.
Faculty Advisor: So think of the processing but instead of salt crystal, you've got gelatin particles.

Now that Shelly understands this possible solution, she begins to modify the problem space, populating it with new questions and tasks, but Andrew sees their task (feasibility research) as nearly complete:

Shelly: I think that's really a good idea.
Andrew: At least it's a start...
Shelly: That's a start
Andrew: And then we are done. Because they'll take care of.
Shelly: Now we can look at into a lot of stuff with this. There is a lot more that we can do.
Faculty Advisor: There is good to look at polymers, what it needs to photo polymerize. [Shelly: photo polymerize]
Shelly: How to uniformly distribute the stuff, how to mechanically make the gelatin fuse into the…

The Faculty Advisor offers further advice on this question:

Faculty Advisor: You're gonna want to go and look at , that are like syringes, and it's like they have, like if you want to reconstitute immediately, they have the reconstitution solution in one side and they have, the whatever your reconstituting in the other side, so like you screw them together and swish, hush, back and forth. […] it's like a double syringe.
Shelly: So, like you, you make like of sprayed really thin layer of polymer then sprayed thin layer of the gelatin particles and then overlay.
Faculty Advisor: No, no, I am saying when you wanna make whatever you are going to attach to your sprayer.
Shelly: Aha.
Faculty Advisor: You've got your polymer in water, on one side.
Shelly: OK, so two different things combined into one sprayer,
Faculty Advisor: Well what, what you do, is you-
Andrew: And then swish them.
Shelly: And mix them together.

At the end of the meeting with the Faculty Advisor, Andrew and Shelly ask for more information about the expert who'll be visiting:

Shelly: Do you know him personally?
Faculty Advisor: Oh, yeah, he was in graduate school and I was an undergrad […]. Oh, yeah I know [him].
Shelly: Would you introduce us?
Faculty Advisor: Sure, like-
Shelly: Really?
Faculty Advisor: Yeah.
Shelly: Oh, that would be awesome.
Faculty Advisor: Let me see, Okay,
Shelly: Thank you very much!
Faculty Advisor: You want me to see if he has half an hour on his schedule?
Shelly: That would be great!
Faculty Advisor: Okay.
Shelly: You're amazing [Faculty Advisor laughs, writes email to them] It's all about who you know and who you know who they know.

Andrew attends the lecture given by the expert and briefly meets with him. With his team, he relates this interaction which served to confirm the feasibility of their new solution. After conducting further research to make sure it really would be a viable option, they explain this solution to their sponsor. Their sponsor was very happy with this idea and the team was able to develop a proof-of-concept prototype.

In chatting with the team after presentation one month before the end of the project, I decide to ask Shelly to explain the Drano analogy, saying that I don't understand how it is applicable. She locates a video on Youtube of a Drano product in which two solutions are poured out and mixed together, instantly foaming up, a very apt surface analogy for their project, though she never explored how the foaming was accomplished. What is revealed as well, however, is that none of her team mates knew of this product either, though they had never asked. Later that week, they reflect on this when Lissa mentions having seen an advertisement for it:

Lissa: Oh, I saw a Drano commercial. [all laugh]
Shelly: Did you? Where was it- did you see with the?
Lissa: It's called like some foam snaking something or other.
Clint: Oh my. [laughter]

Lissa: [garbled in laughter]
Andrew: All right we need to Youtube this - I haven't seen this
Shelly: I wanna see it.
Lissa: It's, it's a new commercial.
Shelly: It is? No I saw it way back in the 90's or something.
Lissa: It's liquid then it was foam! I was like "oh my god" I started laughing.
Shelly: See?
Shelly: It was like two different sections right?
Lissa: Yeah.
Shelly: And it poured out?
Lissa: Yeah.
Shelly: That's so great. [laughter] I'm tellin' ya!
Andrew: Something tells me when she whenever she mentioned Drano our team was like, what was she talking about?? [Shelly laughs]
Lissa: We were like what was she talking about? [laughter] Now I know!
Shelly: But does it like make sense?
Lissa: Yeah!

Though this analogy did not help them when they hit an impasse, they were able to negotiate it swiftly because of the expertise of their mentors. They received scores of four (out of five) from experts on how they applied factual and conceptual knowledge and on how innovative their solution was. To understand their learning and process, however, it is critical to consider them with their network.

The sponsor, who has sponsored several projects and is known to have high standards, was pleased at the final presentation. The support from various mentors, as well as the help-seeking displayed when Shelly asks the faculty advisor to introduce them to the expert enables the team to be successful in their design process. The friendly interactions within the team and the fact that the team members consistently kept each other up-dated on sub-task progress meant that they were able to renegotiate tasks as changes were required and also able to understand the individual contributions of each team member. They were flexible in their tasks, altering them as the problem changed.

Diversity in Design Process and Strategies

These vignettes provide glimpses into the diversity of novice design process, particularly with regard to how students interact with their mentors. By considering these observations I can begin to describe different strategies teams employed. Initial synthesis of this showed qualitative differences in how teams interacted, with some teams spending time negotiating design tasks collaboratively and other teams delegating tasks without understanding how the tasks interrelated. For example, in team 2.1, the Ally is given tasks that seem disconnected to larger project, such as financial analysis and membership levels. This disconnect shows up when the sponsor questions Jeff about her work: he does not know what she has been doing or why she has done it. Likewise, Ally does not understand how it relates to the project and her initial proposals are rejected by the sponsor.

Conversely, in team 2.2, the team mates strategize about the problems they face, whether it relates to trying to down-scope their project, representing their project on a PowerPoint presentation (they even ask me to help them make decisions about their presentation), or deciding who will work on sub-tasks of their project.

Another clear difference between the two teams is the interaction with the mentors. Team 2.1 ends with a near hostile interaction with their Faculty Advisor, and though Jeff attempts to stay in contact with their busy sponsor, he struggles to translate her requests to Ally. By contrast, team 2.2 is well supported by their mentors and actively seeks out further mentorship, as when Shelly asks their Faculty Advisor to introduce them to a visiting expert. They maintain amicable relationships with their mentors throughout their project, even when they are attempting to down-scope their project.

Observations of other teams also hint at other potentially important strategies teams might employ as they learn to design. For instance, at the end of their final presentations, the course instructor asked each team to explain how their project went, what was challenging, and to explain how they worked. Though most teams described a process of negotiation sub-tasks to be completed individually or in pairs, there were distinct exceptions. Some teams described redundancy, treating the project as familiar study groups in which they each worked on the project individually before bringing their solutions together. This type of group rather than team work did not seem to be satisfactory, though this would require further research. Additionally, one team described a process in which the student who knew most about a task would complete it but also teach the others how to do so. This type of apprenticeship model may be inappropriate for the professional design studio, but for the design classroom, may be an appropriate strategy for learning content and design process. Further research is needed to more fully understand how students apply these strategies as they learn to design, but clearly, it is a diverse process occurring through interactions within the team as well as well as with mentors.

Conclusions

This pilot study investigated how student teams learn to design; I employed mixed methods, combining traditional individual measures of classroom practices, team level measures, and qualitative study of teams. Determining how learning experiences should mirror the community of practice can be difficult, but my pilot study findings suggest that inducing the need to consider multiple perspectives via Voice of the Customer is critical to design learning. Because Cohort One did not feel authentically invested in the mini project, they did not effectively learn to value the Voice of the Customer. The authenticity of the sponsored project and of the redesign project helped the students to value the Voice of the Customer and to understand the intrinsic design requirement of incorporating customer needs.

Experiences such as the sponsored project and even the redesign project provide opportunities for learning procedural aspects of design. Given that some universities do not have the resources for sponsored projects, this finding has implications for structuring less authentic design experiences: By allowing students some autonomy in identifying, through customer needs, a redesign path, students become authentically engaged in design.

Design problems allow students to construct their own understanding; this is evidenced by results from a validated instrument showing that students perceive that the problems they are solving are relevant and that they have some control over how they are learning. However, I have yet to relate this to other outcomes, such as Innovation and Efficiency. Expert sorting of designs revealed that Innovation breeds Innovation.

There appear to be multiple strategies students employ as they learn to design but without taking advantage of the distributed resources of the team and negotiating design tasks, success will be limited. In fact, the affordances of working in a team may be eliminated altogether. It is critical to consider the extended design team, that is, the students, the teaching assistant, faculty advisor, sponsor, and any other mentors involved in the process. If students are not adequately supported by mentors who pose conceptual questions, who help them gain access to needed resources and people, design success will be limited. Further qualitative research on team design process learning could help to clarify these tentative observations, or to extend it into a model, which is a goal of the main dissertation study.

These findings are promising; however, variance across Cohorts and within Cohorts is as yet unexplained on several measures. The lack of connection between measures speaks to a missing aspect as well. The qualitative data make it clear that learning in this context is fundamentally social and interactional. This is not at all represented in the statistical models. The main dissertation study therefore involves incorporation of measures of interaction.

Further Research Questions

Results from pilot study questions led to further research questions. Pilot research indicated that teams interact very differently, both in terms of how they divided tasks and in how they interacted with mentors. Many individuals are part of the system that results in a team's design, including the teaching assistant, faculty advisor, class professors, sponsor, and in a few cases, even the researcher. This aspect was not captured nor represented in the pilot research. Furthermore, the lack of correlation between Early Efficiency and Final Innovation is of interest because it runs counter to traditional instructional sequencing.

Broadly, the research questions for the main dissertation study focused on examining whether the design class provided a setting that supported students in developing towards being innovative and efficient designers, and furthermore, how students in teams learned to design and learned as they designed. Research questions related to the former were primarily addressed through statistical models, whereas the latter were examined via qualitative research.

A goal within professional engineering practice is to produce innovative design solutions, however, it is not entirely clear yet how to teach for innovation (Clough, 2005). Students need opportunities to learn efficiency as well, and to gain experience with the cognitive and affective aspects of design. Pilot qualitative research demonstrated diversity in how students interacted with their mentors; by incorporating measures related to mentors and team interactions, a clearer understanding of how to support such student learning will be possible. There are numerous quantitative components to this question.

Statistical models provide a sense of trends, but researchers generally assume that process and product are necessarily tightly coupled. It may reasonable to assume tight coupling between process and product in the context of collaboration because the product should represent the joint efforts of the team (Boujut & Laureillard, 2002). However, product-based analysis masks the diversity of processes that may converge on a singular outcome or product (Mercier, Goldman, & Booker, 2008).

Design process is heterogeneous and complex, and poorly understood in terms of student learning, making this assumption somewhat tentative. Because of the authenticity and complexity of this context, with teams designing different devices, I focused on a meta-level aspect: how teams negotiate design impasses (impasses will be defined and contextualized further in Chapter 6). Particular research questions about case study teams were emergent:

- How can I quantify interaction within design teams and their mentors?
- What is the relationship between how Innovative and Efficient team designs are judged to be by experts and measures of design skills, perceptions of learning opportunities, perceptions of mentors and team mates, and team cohesion?
- How might I characterize novice design problem scoping and the transition towards being solution focused?
- How might students in teams interact and leverage resources and mentors and as they learn to design products, and how does this reflect, contradict, or extend statistical models of whole class trends?

Design process extends across individuals and over months with the problem and solution coevolving during the process (Dorst & Cross, 2001). Such a complex phenomenon naturally has aspects that lend themselves to quantification and others to observation. Therefore, these were investigated through triangulation of mixed methods research, discussed next in Chapter Four.

CHAPTER FOUR: DISSERTATION STUDY METHODS

Triangulation

When conducting statistical research, researchers often make an implicit assumption that the outcomes/products truthfully represent the process/learning. As I seek to answer questions about learning design process, simple application of multiple methods is not sufficient to achieve understand this phenomenon; for this to occur, triangulation is required. Triangulation affords the opportunity to examine the relationship between process and product, a need called for (Spada, 1987) but not generally met. I employed a concurrent triangulation design, meaning that the data were collected concurrently with approximately equal priority placed on all types of data, and with integration occurring throughout, though with a particular emphasis during interpretation (Creswell, Clark, & Gutman, 2003).

In the context of social science, methodological triangulation has been taken to mean the use of two methods to converge on one (more valid) interpretation. This understanding tends to assume a realist ontology such that non-convergent findings may be rejected as measuring differing things (Sale, Lohfeld, & Brazil, 2002). Rather than adopt a specific stance that all of my data sources necessarily converge on a singular understanding of a phenomenon or else are invalid measures of said phenomenon, I adopt a pluralistic stance, assuming that *design process* comprises contextualized phenomena which maybe be interpreted through various data. Further, inclusion of multiple types of data affords greater access to complex phenomena, with differing methods revealing differing aspects of the process. Rather than assuming I am measuring the same thing with two methods, I assume that I am measuring different aspects of a complex phenomenon that may not be fully apprehended.

While strong paradigmatic and methodological stances of the past have created polarized views within educational research, a more integrated view has emerged in recent years (Teddlie & Tashakkori, 2003). This integration of methods leverages the strengths of qualitative and quantitative methods, and commonly rests on a pragmatic (anti)philosophical stance (Johnson & Onwuegbuzie, 2004). Pragmatism involves considering the potential outcomes of addressing research questions with various methods, and applying the methods that are contingent (Maxcy, 2003).

One of the reasons to adopt a qualitative view rather than a reductionist view is to represent the complexity of the world. “Epistemological and methodological pluralism" associated with mixed methods represents a potentially stronger way to achieve this goal (Johnson & Onwuegbuzie, 2004). While some researchers consider the rift too large (Guba, 1990), others consider it constructive to consider the similarities across paradigms. For instance, research generally involves reliance on empirical observations and description of data, the construction of explanatory arguments, consideration for causes of findings (Sechrest & Sidana, 1995), and demonstration of validity concerns (Sandelowski, 1986). Additionally, philosophical agreement can be found across the commonly employed paradigms (except strong positivism and post-modernism): reason is subjective and varies across individuals; perception and interpretation are theory-laden; multiple theories may fit data; hypotheses are theory-laden and as such cannot be fully tested; probabilistic evidence can only approximate; research is a social undertaking and therefore includes the subjective views and preferences of the researchers.

As a guiding principle for mixed methods research, the researcher should combine appropriate methods with a goal of minimizing weakness of each while finding complementary strengths (Johnson & Turner, 2003). The interplay between methods, which in this study are social network analysis (SNA), hierarchical linear modeling (HLM), and qualitative research, serves to enhance each other method (Figure 4.1). Social network analysis allowed me to bring a measure of interaction into my statistical models, which provide trends to contrast and extend through case study research. Social network analysis also allowed me to create sociograms representing interactions, and these formed the basis for hybrid qualitative/qualitative graphs representing case study teams over time, and evolved in conversation with qualitative analysis of teams negotiating an impasse. These graphs then served as a means to explore connections between design process and product, a relationship assumption made by researchers in most statistical models. In this case, I examined efficient and innovative aspects of design process that teams employed and question whether these necessarily relate to efficient and/or innovative design products.

Figure 4.1. Triangulation of data/methods, with conclusions emerging from the centroid

Next I describe the participants and context of the main dissertation study in more detail, and then expand upon how the methods I chose were employed towards triangulation of data and findings.

Participants and Context

The participants of this study are senior bioengineering students enrolled in the capstone, year-long design class at The University of Texas at Austin. Students elected to participate in the study, and were informed that they could withdraw at any time. Cohort Two, which was also included in the pilot study, comprised students from fall 2006 through spring 2007 and Cohort Three comprised students from fall 2007 through spring 2008. Somewhat less than half of the students are female, close to half are Caucasian, and in both cohorts there is a sizable Asian population (Table 4.1). Approximately one fifth of the students are non-native English speakers, and less than half have parents born in the USA (Table 4.2). Students' father's educational mode is graduate school followed closely by graduation from college, whereas mother's educational mode is the reverse (Table 4.3). Most of the students are public school educated with high GPAs (approximate average 3.8) and have moderately high college GPAs (3.54 average) (Table 4.4).

Table 4.1. Ethnicity of students in Cohorts Two and Three

	Percent Female	Caucasian	Asian	Latino	African American
Cohort Two	45%	50%	47%	3%	0%
Cohort Three	38%	45%	36%	16%	3%

Table 4.2. Demographic Characteristics of Cohorts Two and Three

	Non-native English Speaker	Parents born in USA	Parents Not born In USA	One Parent born in USA
Cohort Two	22%	39%	50%	11%
Cohort Three	21%	48%	30%	23%

Table 4.3. Parental School Demographics of Cohorts Two and Three

		Less than High School	High School	Some College	College	Graduate school
Cohort 2	Father	2%	8%	23%	27%	39%
	Mother	5%	6%	19%	45%	24%
Cohort 3	Father	3%	8%	10%	30%	49%
	Mother	1%	15%	15%	35%	33%

Table 4.4. College attendance and past educational achievement of Cohorts Two and Three

	1st Gen Attendee	1st gen Graduate	Public HS	Ave SAT M	Ave SAT V	HS GPA	UT GPA
Cohort Two	10%	13%	87%	720	662	3.85	3.54
Cohort Three	6%	9%	90%	714	687	3.79	3.54

This study follows the second and third times this course has been taught, as the bioengineering major is a new major. Design teams were composed of three to five students who were selected by the course instructors. In accordance with common practice, the teams were formed using the Myers Briggs (Dutson, Todd, Magleby, &

Sorensen, 1997) instrument, however, there is evidence that this is not a useful tool for predicting extended interactions and does not prevent "personality conflicts" (Emanuel & Worthington, 1989). The instructors made sure that non-native English speakers, which make up a sizeable minority, were distributed across teams.

The class is taught in two consecutive semesters by two different professors. The four teaching assistants play a large role in facilitating the students' learning; the TA's had approximately 100 contact hours with the teams and helped with assessment of students' work. Additionally, teams were mentored by faculty advisors and their sponsors. This yields a complex pattern of interactions officially endorsed by the course structure (Figure 4.2). However, it also masks the true pattern of interaction, as many teams seek out or are guided towards many other mentors (Figure 4.3).

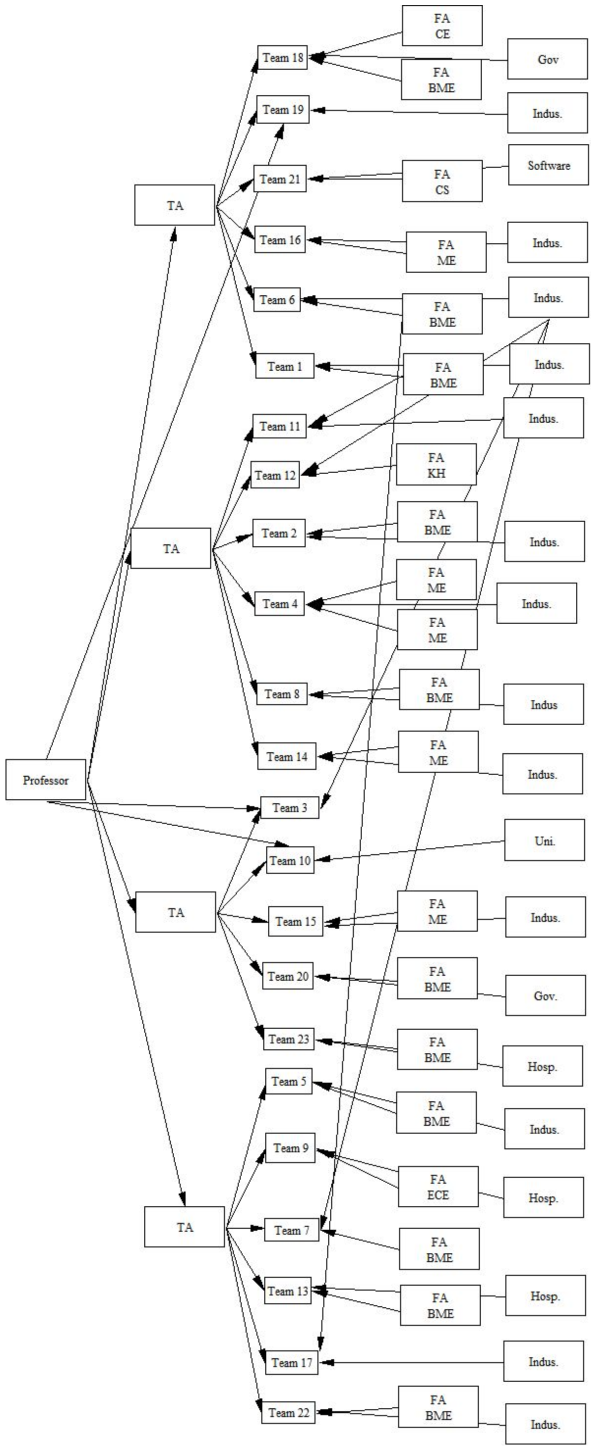

Figure 4.2. Official interactions within the design course for Cohort 2

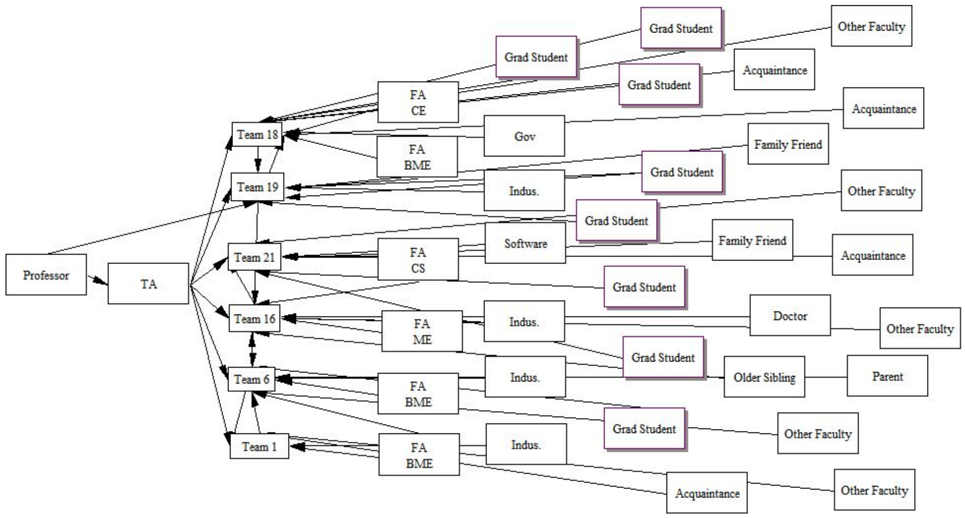

Figure 4.3. Hypothetical representation of realistic interaction complexity for a subset of teams.

Both cohorts completed a two-month preliminary redesign project prior to beginning their sponsored project (Figure 4.4). For the redesign project, teams selected biomedical devices, such as nicotine patches, inhalers, and pregnancy tests and redesigned some aspect of the device. The device had to be approved by the professor, and though the redesign direction did not go through an approval process, the professor provided many teams with guidance and the TAs sought advice from the professor regarding the redesign directions when questions arose. Simpler devices were rejected as being difficult to redesign. The redesign had to functionally alter the device, and therefore aesthetic redesigns were not permitted.

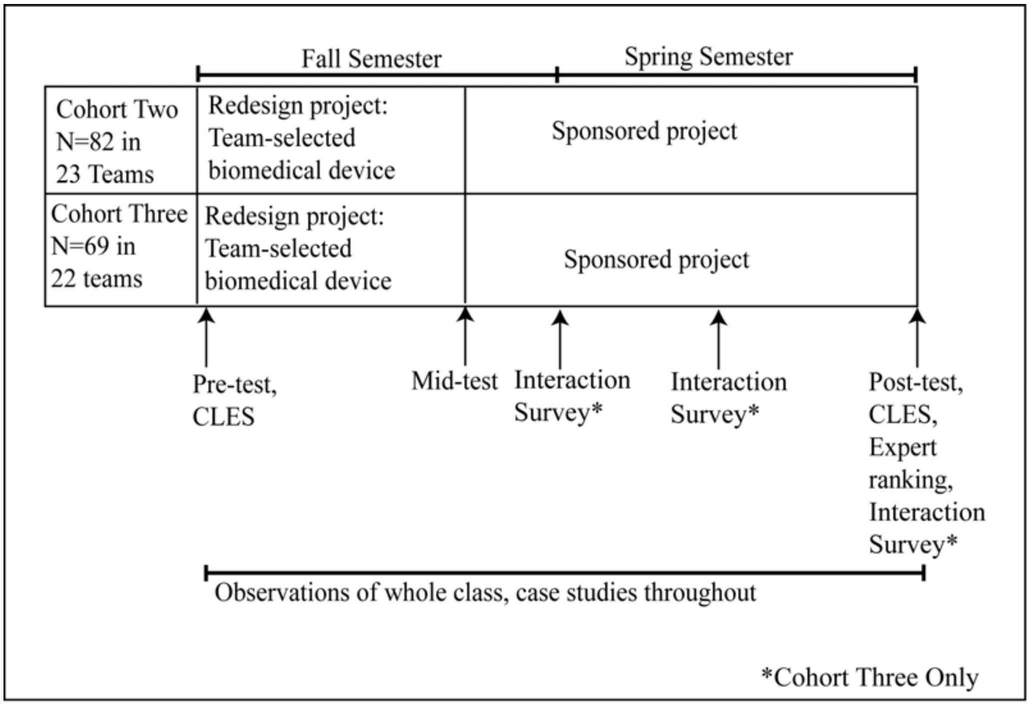

Figure 4.4. Course format and data collection schedule

The redesign process was structured by the use of various tools and assignments:

- Gantt charts are projected timelines, and are updated throughout the project;
- Voice of the Customer, in which students identified and interviewed several potential customers, including a variety of types of customer, such as a doctor, a nurse, and a patient, then coded the interviews to determine customer needs;
- A mission statement in which the teams write a statement about their goals and how they hope to accomplish them;
- A Functional Model, in which the device is modeled based in inputs and outputs of energy, information, and materials;
- Benchmarking, in which students provide a review of literature and patents relevant to their redesigns ;
- House of Quality (HOQ), in which customer needs and other design aspects are contrasted to determine tradeoffs as part of Quality Function Deployment;

- Assembly Instructions, in which the students predict how the device functions, then dissect their device, then provide an exploded diagram showing how it is assembled and how it works;
- Ideation, in which the students choose a methods for coming up with possible solutions to a design problem they are having;
- Estimation results, in which students estimate feasible redesign options;
- Pugh Chart, in which feasible redesign options are contrasted along several outcome dimensions; and
- Oral Presentations, in which the teams present their redesigned device

After completion of the redesign project, the teams were selected by sponsors to design a biomedical device or protocol. The projects came from hospitals, industry, government, and universities, and were varied in terms of difficulty, though all presented challenging problems (see Appendix B for complete listing of projects). Additionally, the skills and content necessary to complete a design may or may not have been a part of the degree program. For example, projects involving circuits may have been challenging because these students do not have extensive experience with circuits, whereas the same project may have been more straightforward for an electrical engineering student.

In the remainder of the Fall semester, students were given instruction during lectures and completed activities related to their sponsored design projects, and similar to those completed for the redesign project. Activities included Gantt Charts, Pugh Charts, Ideation, House of Quality, Voice of the Customer, various oral reports, progress reports, and final reports and presentations.

The students typically do little formal team work prior to the design class as part of their coursework. Therefore, the intense teamwork the students experience in this course has the potential to provoke new learning of "soft skills" such as interaction, communication, and team work (Seat & Lord, 1998). The lens of community-centeredness (Bransford, et al., 2000) is an important one for understanding how the students learn in this course. The fundamentally social nature of learning (Kuhl, 2004; Lave & Wenger, 1991; Vygotsky, 1978) is a critical but missing aspect from statistical models of learning.

I next explain the measures used and how each method was used, and then explain how I triangulated data sources and findings.

Measures related to Design Learning and Interactions

Data Collection and Instruments

Pre and mid-tests (Appendix C) and surveys (Appendix D) were completed at an individual level, providing data on how students design, how they interact, and what their beliefs are about design and collaboration. Team level data, beyond contextual variables (averages of individual measures) include Cohort membership and measures of Efficiency and Innovation of design work completed by teams. These measures are described in more detail next.

Design Skills Test

The design pre- and mid-test employed the same challenging question each time, and has been used for all Cohorts. It includes a challenging design question (Appendix C) in which the students are told that they are not expected to be able to complete it, but that we are interested in how they begin designing such a problem. This question is used to examine how student thinking changes with experience in design, and involves designing a device for treating hypothermia in war conditions, given several constraints. The pre-test is given in the first week of class and the mid-test is given following completion of the redesign project.

A coding scheme (Appendix E) based on expert performance and expert evaluation of student performance was developed. The codes of particular interest include Feasibility, Diagram, and Voice of the Customer (VOC). Using this coding scheme, twenty percent of the tests were coded for inter-rater reliability (92%). Feasibility reflects mostly factual aspects, Diagram is conceptual, and VOC involves multiple perspective taking as students represent the varied needs of diverse customers or end users (for example, doctor, nurse, field medic, patient).

Innovation and Efficiency of Design Products

Experts provided scores of Innovation and Efficiency for student design products. A design may satisfy technical requirements yet not be an innovative solution. Both aspects are important for designers and valued by the community (Martin, et al., 2006; Martin, et al., 2005; Pandy, et al., 2004; Petre, 2004; Petrosino, et al., 2006). The Early design products (project definitions) and Final designs were both ranked and sorted along the adaptive expertise dimensions of Efficiency and Innovation (Schwartz, et al., 2005) by the spring course instructor, who is familiar with these constructs (Appendix F). Additionally, reliability on the sorting was established with other experts (89%) and by asking the instructor to re-score the same group a second time (93.5%).

Constructivist Learning Environment Survey

The Constructivist Learning Environment Survey (CLES) was administered. This instrument has been validated through several studies (Nix, et al., 2004; Taylor & Fraser, 1991; Taylor, et al., 1997; Taylor, et al., 1994). The CLES measures perception of personal relevance, shared control, critical voice, and student negotiation (Appendix G). Traditionally, the instrument also includes a measure for the Nature of Science, but as this is clearly not applicable and in the absences of a well validated scale for Nature of Engineering, this facet was omitted from the measure. The survey is a 5-point Likert scale (1=Almost Never; 2=Seldom; 3=Sometimes; 4=Often; 5=Almost Always). Six questions cover each category. Students completed the survey individually; once as a pre-measure assessing prior engineering coursework and once as a post measure assessing the design class. Student Negotiation is employed as an individual level measure to corroborate the use of social network analysis to produce team level scores of cohesion. Student Negotiation scores reflect opportunities to compare and explain ideas, which should relate to team cohesion.

Measuring Interaction

Missing from statistical models in the pilot research were measures related to interaction. This is true of most statistical models and therefore not surprising that I did not initially include it. However, I realized that in striving to represent a fundamentally social process, this is a serious limitation to understanding. Student level perceptions of interactions, and team level summary statistics of interactions may explain variance in other measures. In order to understand how the design teams differ, it is critical to consider their interactions, both within team and with mentors. Dimensions of interaction initially investigated included frequency and duration of meetings though these were dropped when they did not relate to other variables. This left dimensions related the perceived value of interactions and peer relationships. That these facets, as opposed to frequency and duration, relate to other variables is not unexpected as some interactions may occur frequently but be unproductive while others may be rare yet impactful.

Surveys were given to Cohort Three at three time points during the spring semester (early February, March, late April) to provide snapshots of interactions within teams and with various mentors (Appendix H). Surveys were completed individually and afforded students the opportunity to mention problems they were having. Surveys included questions regarding the value of interactions along three facets, each associated with Likert items (1=strongly disagree; 5=strongly agree) and open items. Students were asked to report for each most recent interaction with each mentor the following:

- This meeting changed my understanding of our design project;
- This meeting was productive;

- Significant progress was made towards our design project because of something that occurred at this meeting.

These will henceforth be referred to in brief as Changed Understanding, Productive, and Progress.

Peer evaluations (Appendix I) were collected at four time points during the year, three of which corresponded to the surveys. These were completed individually and provide another indication of how the team is working together. The peer evaluations contain many facets, but only those related to overall contributions were used for this analysis, described next.

Preliminary Data Analysis: Social Network Analysis

Generation of team-level summary statistics related to interaction called for specific techniques beyond simple averaging or variance. Instead, I employed social network analysis (SNA) which is an attempt to formalize and empirically explicate relationship ties and their patterns (Wasserman & Faust, 1995). Systemic relationship ties are measured. Individuals within the network are viewed as interdependent and therefore are seen to influence each other. Ties between individuals, in this case, are evaluative and directional. Though ties are more commonly dichotomous (present/absent), in this case, I used values associated with ties reflecting the Likert ratings from the surveys.

Social network analysis has been used in engineering contexts previously to identify communities of practice and changes over time in communities (Borrego, Osborne, Streveler, Smith, & Miller, 2007), to examine relationships between universities and schools as a result of outreach programs, and as a means to examine impacts on community from a workshop (Fincher & Tenenberg, 2006).

As is generally the case in SNA, I assume that the relationships between team members and mentors contribute to the variance in other outcomes and that an individual’s recall is accurate. With the case study teams, I was able to, though observations, corroborate these reports. Although inaccuracy may be problematic, it tends to be related to uncommon and less impactful relations, which are generally of less interest to the researcher (Wasserman & Faust, 1995).

Validity issues common to quantitative research methods also hold for SNA, such as construct and face validity. Reliability measures must be considered differently, however, because social measures cannot be considered stable within a social network; they are dynamic and defined by action. I asked questions in alternative formats to provide a proximal measure of reliability. Measurement error was reduced by avoiding fixed number questions (for instance, use "Name the most important", rather than "Name the two most important) (Wasserman & Faust, 1995).

Though more commonly conducted in square matrices (Table 4.5), the structure of my data indicated the need for a two-mode model, in which students in design teams provide scores for each other, but also provide scores for their mentors (Table 4.6). The square within-team data are peer evaluation data. The rectangular matrices are multiplex, meaning that several layers of data that were considered: Changed Understanding, Productive, Progress.

Table 4.5. A square matrix of students in a design team

L^1	n_1	n_2	n_3	n_g
n_1	-	X_{12}	X_{13}	X_{1g}
n_2	X_{21}	-	X_{23}	X_{2g}
n_3	X_{31}	X_{32}	-	X_{3g}
n_g	X_{g1}	X_{g2}	X_{g3}	-

Table 4.6. A rectangular matrix, in which n1-ng are students in the design team, and in which m1= TA; m2=FA; m3= Sponsor; and m4-mh= other mentors

L^2	m_1	m_2	m_3	m_4	m_h
n_1	X_{11}	X_{12}	X_{13}	X_{1g}	X_{1h}
n_2	X_{21}	X_{22}	X_{23}	X_{2g}	X_{2h}
n_3	X_{31}	X_{32}	X_{33}	X_{3g}	X_{3h}
n_g	X_{g1}	X_{g2}	X_{g3}	X_{g4}	X_{gh}

I desired to create team level summary statistics of the facets described in the interaction survey: Changed Understanding, Productive, and Progress. SNA produces several options for examining relationships and roles based on relationships, though I relied on a network/team level measure called group degree centralization (C_D), which summarized the variance in strength of ties each individual has to others. This is used as a measure of cohesion (Wasserman & Faust, 1995) and will henceforth be referred to as Cohesion. It is commonly calculated as follows:

$$C_D = \frac{\sum_{i=1}^{g}[C_D(n^*) - C_D(n_i)]}{[(g-1)(g-2)]}$$

where $C_D(n^*)$ is the largest observed value of $C_D(n_i)$, the actor level degree centrality index, and g is the number of individuals in the network. $C_D(n_i)$ is generally calculated as the number of all ties an individual has, but in the context of a weighted network, this is the sum of all ties. Note that this can be thought of as a calculation of the variance of individual degree centrality. As such, higher scores (0.8-1) correspond to higher variance and lower Cohesion, whereas lower scores (0-0.2) correspond to lower variance and higher Cohesion. To put this into the current context, Cohesion (C_D) is calculated for each team as a sum of the variances of Likert (one to five) ratings the team members have given to one another and to their mentors, and normalized with regard to team size (such that if a team has three or five members, it can easily be compared to those with four members).

My networks are weighted rather than populated by more commonly used binomial data. In weighted networks, Cohesion describes the strength of relationships, not the presence and absence of relationships, though absence of a relationship may still be denoted with a zero. This, however, leads in to a problem: how to represent missing data due to non-response. Research has demonstrated that this results in an underestimate of actual clustering, resulting in an inflated measurement error (Kossinets, 2006). The advantage of using a weighted network as opposed to a binomial network is that I could more easily introduce a correction factor for actors with incomplete response rates, specified as the percent of total possible links reported. Rather than introducing a random variable or an average of the actor's other ratings as is suggested for binomial networks (Carrington, Scott, & Wasserman, 2005) (the former of which is problematic in small networks as it could produce skew and strongly affect the network, the latter of which is problematic because I am assuming that there is not necessarily uniformity in scores over time) I introduced a correction factor that served to address the underestimate of clustering. This factor is placed directly in the formula as follows:

$$C_D = \frac{\sum_{i=1}^{g}[(L_O/L_E)(C_D(n^*) - C_D(n_i))]}{[(g-1)(g-2)]}$$

where $C_D(n^*)$ is the largest observed value of $C_D(n_i)$, the actor level degree centrality index, L_O is the observed number of links between actors, L_E is the expected number of links between actors given complete response rates, and g is the number of actors in the network. $C_D(n_i)$ was calculated as sum of all ties.

This correction factor carries with it certain assumptions. First, it assumes that there is not a consistent trend in the missing data. This assumption is reasonable as for most instances, there is only one survey missing per team. Secondly, it assumes that the missing data are random and not due to specific causes and do not indicate something about the team's cohesion. This assumption is somewhat more problematic, as there is no simple way to determine the accuracy of this assumption. However, because past research has demonstrated that missing data tends to underestimate Cohesion, this is an assumption I have made, but is a limitation to the findings. Furthermore, in order to use the Cohesion scores for teams, it was more important that they lay within a consistent range, rather than an artificially expanded/skewed range.

When Cohesion was calculated without this correction factor, missing links are treated as zeros, and this has a tendency to increase the apparent dispersion (and therefore to underestimate the clustering), resulting in scores that occupy a different space (0.9-1.6) as compared to those with few or no missing data (0-1). When calculated with the correction factor, all scores occupy the same range (0-1). By using this formula, I created nine Cohesion scores derived from the three facets (Changed Understanding, Productive, Progress) arrayed across three time points.

Teams with Cohesion scores closer to zero have tighter clustering of scores, meaning that actors have scored each other and their mentors in a similar manner, whereas teams with scores near 1 have scored each other and their mentors with greater variability. Note that having high Cohesion does not, however, indicate whether the scores were uniformly high or low. This aspect is particularly troubling to some, that a team could agree that all interactions are quite poor. High Cohesion cannot be assumed to equate to better design outcomes, though it does reflect something about how the teams are interacting at a point in time. Because this work is exploratory (in terms of when and how Cohesion might be important) and there is little research to direct a model, an exploratory technique was used to build a Hierarchical Linear Model, discussed next.

Data Analysis: Hierarchical Linear Modeling and Regression

In some cases, I take the team as the unit of analysis. When predicting team level outcomes, I therefore include team averages of student level measures to predict team level outcomes. In such cases, I employ standard regression analysis.

My research questions and context involve students nested within teams, meaning that each team's experience may be assumed to contribute variance and to influence team and student level outcomes because students in teams cannot be considered to be independent from one another. Without including the upper levels of variance, I would risk increasing the Type 1 error rate for analysis. Not considering the impact that upper levels contribute to variance also leads to aggregation bias and concerns over the unit of analysis, such that impoverished models and related hypotheses abound.

I employ Hierarchical Linear Modeling (HLM), an extension of traditional approaches for nested data, allowing examination of relationships between variables and across teams. The random factors in the model are assumed to be normally distributed. Univariate normality is assumed for participant error variance and multivariate normality is assumed for team level error variance. Error variance is assumed to be constant across observations. For each level, it is assumed that the systematic contribution to variance is fully specified and that appropriate interaction terms are included.

When predictor variables vary across teams and within teams, HLM allows for the separation of these effects. Typically, HLM includes dependent and predictor variables at the individual level and predictor variables at the team level. The procedure involves generating regression equations for individuals within teams, and these are compared with the team level variables. Dependence within teams is accounted for by the intraclass correlation. An advantage of HLM is that no extra measures are required to balance team size. This is useful as some of the design teams have three members and some have four.

One of the limitations of HLM is the interaction between sample size, number of levels, and power. Though there are rules of thumb for sample sizes, there is no rule for determining the number of levels that contribute significant variance, and with smaller sample sizes, greater numbers of levels will result in less power. Relatively large sample sizes are required to achieve power (Maas & Hox, 2004, 2005; Reise & Duan, 1999). My team level sample size is small enough to cause concern with regard to estimates of team level variance, which may be underestimated (though student level estimates should not be much impacted) (Maas & Hox, 2005).

I explored relationships of explanatory variables to outcome variables in two level models. Level one included student characteristics, such as SAT Verbal Score, Underrepresented Minority status, CLES Scores, Design test scores, ratings of mentors, and team membership (Tables 4.7 and 4.8). Level Two includes team level variables, including cohort membership, TA, Cohesion, and expert scoring for Innovation and Efficiency though not all variables contributed variance.

Table 4.7. Measures For all Cohorts

	Ratings by Experts				Constructivist Learning Environment Survey				Pre and Mid Design Test		
	Early Project Definition		Final Design								
Level:	Efficiency	Innovation	Efficiency	Innovation	Personal Relevance	Shared Control	Critical Voice	Student Negotiation	Feasibility	Diagram	Multiple Perspective Taking-VOC
Team	X	X	X	X	Ave.	Ave.	Ave.	Ave.	Ave.	Ave.	Ave.
Student					X	X	X	X	X	X	X

Table 4.8. Measures for Cohort Three

Level:	Peer Evaluations	Interaction Surveys
Team	Ave.	Ave.
Student	X	X

Because the research on Cohesion in particular is exploratory and cannot be well guided by theory in terms of when this type of measure of Cohesion would likely impact outcome variables, I conducted an exploratory analysis of potential level two predictors, namely, the three facets of Cohesion across three points in time.

While this analysis provides models related to team design learning, as mentioned at the onset of this chapter, how students learn design process may be best understood through triangulation of methods. Therefore I also employed qualitative research, described next.

Qualitative Research

Qualitative research is appropriate when the research questions seek to uncover how or why learning occurs (Mertens, 1998). Qualitative methods are particularly appropriate for studying in-situ phenomena. In order to better understand how student teams learn to design, I employ case studies and narrative analysis. By selecting multiple cases, which in this context refers not to individuals but to design teams, I investigated interaction (Yin, 2003) in bounded phenomena (Merriam, 1998), i.e., design projects. I began my research as case study research, but adopted aspects of narrative research as well. This process is described next.

The diversity in team projects and resultant activities did not lend themselves to micoranalytic analysis, particularly given my desire to understand the broader learning processes. I therefore began by considering macro level events from the case study teams. I initially framed these events by the language of expert design process: problem scoping, ideation, defining the problem, optimization, and so forth. When I tried to locate these within the case study teams, I struggled for two reasons: Design is iterative and therefore it can be difficult to predict when and how frequently even an expert team may engage in such activities and how timing/ordering within the process might alter or affect them; and furthermore, with these novice teams, it seemed to me that a number of these aspects were wholly missing because the teams spent a greater percentage of time on problem scoping. Understanding how and why this occurred therefore became the focus of my qualitative analysis.

In order to understand a process that extends over months rather than hours, I constructed team narratives. Note that this differs from traditional narrative analysis which relies on interviews in which individuals are viewed as living storied lives and asked to recount their stories relating to a critical event under investigation (Elliott, 2005; Labov & Waletzsky, 1967). I constructed narratives using the teams own conversations, initially moving from field notes to full transcripts annotated with field notes, team design work, photos, and surveys before narrowing the focus on a critical event (Labov & Waletzsky, 1967).

Though this is not narrative analysis per se, I draw upon the ideas of narratives and adapt this concept to convey the life histories of the case study design teams as they evolve over the course of the design projects. Narratives are inherently temporal or chronological (Elliott, 2005). Events ordered in time reveal a story, with a plot "formed from a combination of temporal succession and causality" (Elliott, 2005). Critical events may generally not be identified before they occur, rather, they tend to present as recalled within histories. However, within the context of design team narratives, it is likely, due to the challenging nature of the authentic design activity the teams participate in, that critical events will occur during the team lifetime. Within the narratives examined here, all case study teams experienced some sort of impasse. Narrative treatment allows these impasses to unfold chronologically and through team members’ conversations and interactions, to be further understood through cross case analysis and triangulation with other data sources, and finally to be interpreted with perspectives on design and design learning.

Narrative inquiry is commonly conducted via interviews soliciting life stories of individuals. However, in this context, the lifespan of the team is comparatively brief, lasting months rather than years. This affords the firsthand participant observation of many events during the team lifespan.

I therefore constructed narratives of the teams as they negotiated *impasses* within their design process. I define impasse here as a significant barrier to forward progress; a problem that, to the team, seems insurmountable. I observed this in my case studies from Cohort Two, particularly when team 2.2 attempted to renegotiate the scope of their problem. Whereas their impasse was resolved in a matter of a week or two, in most of the cases this is not so, and the impasse prevents them from adopting a solution focused perspective. Rather, the teams tended to spend much time problem-scoping.

Data Collection

For each Cohort, I collected qualitative data on three teams, providing six case study teams, though here I focus on only those teams from Cohort Three. Teams were selected with input from the professors and teaching assistants. For Cohort Two, a list of High, Medium, and Low performing teams was generated by the professor and a team randomly selected from each level. For Cohort Three, the professor and teaching assistants were asked to name their highest and lowest performing teams, to name which teams sought out resources and which did not, to name teams which had projects that would be particularly difficult, and were invited to suggest teams they thought might be interesting to study for other reasons. These data along with results from peer evaluations and a preliminary survey of interactions were put into a matrix to create three levels (high, medium, and low performing), from which teams with all or most members opting into the study were selected.

Teams were observed as they met together, as they worked, and as they met with mentors. It was not possible, as one researcher, to observe all meetings, as some meetings occurred simultaneously. In some cases, teams were asked to audio record a meeting. Most meetings were audio recorded and a subset were video recorded. Not all teams were amenable to video recording. The nature of this in-situ data collection poses limitations on video recording: much of the design activity took place in a room with only one available electrical outlet, and this was commonly in use by a student. Additionally, not all sponsors were comfortable with video recording of materials covered by Intellectual Property (IP). Thus, audio recording predominated.

Informal interviews/discussions emerged during observation, either instigated by the researcher or by the students. The students are curious to know why someone would want to study them; when answering their questions, I have framed my research as an effort to better understand design learning, such that improvements may be made in how it is taught. I was careful to avoid framing the research as contrasting high and low performing teams, because I did not want a team to wonder if they have been picked as a "bad" team. Likewise, I requested the professors and teaching assistants to discount this idea should a student posit it. Informal conversations were also used for member checking and clarification, though the latter was rarely needed as the students tended to assume that I had insufficient understanding of their projects, and would explain and even teach me about concepts, and use me as a sounding board for presentations that were aimed at a "general but intelligent" audience.

Design artifacts, including assignments, design journals, and final design presentations were collected. Photos of the "pool room," the main location in which students meet and interact, were taken at various time points to provide context, but also as potential data.

Data Analysis

Field notes and recordings were reviewed to identify impasses for each team. In all cases these are striking and recurrent issues that significantly delay progress in the design activity of the team. Team narratives were constructed by initially transcribing the conversations leading up and following the course of the impasse, as well as those reflecting on the impasse or the ways in which the impasse was resolved. Transcripts were then reviewed several times, allowing themes to emerge. The themes detail not only the causes of and solutions to the impasse, but also other contextualizing themes for specific case study teams, allowing the team identities and idiosyncrasies to be part of the narratives. I looked for counter examples to these themes, and compared excerpts of transcript related to each theme to decide whether or not they described similar ideas. This macro-level coding allowed me to seek similarities and differences across very different design projects.

Because the sponsored design projects observed covered quite different topics, of varying difficulty, and involved different students, it is difficult to contrast them. By focusing on how each case study team negotiates an impasse in the context of their larger project, I was afforded an opportunity to examine how they interacted as a team and with mentors. The impasses cannot be considered precisely parallel, as they arose at different times and had differing impacts on the ability of the team to move forward with a design, however, cross case analysis of themes related to the negotiation of impasses afforded an understanding of the narratives as framed by theoretical perspectives related to design and learning.

Hybrid Qualitative-Quantitative Sociograms

Representing quantitative data in their complexity, and contrasting such cases yields context for understanding the case study teams and raises further questions. Lloyd and Deasley encourage the use of methods that allow design to be studied as a social process, highlighting ethnographic methods in particular to examine this process "spread over a social network, and through the narratives and discourses that are forged from day to day" (1998, p. 101). Though not explicit in his methods, his description of design process *is* explicitly about social networks, making application of social network analysis and qualitative research together particularly appealing.

The narratives are illustrated by incorporating and interpreting the sociograms produced through SNA. These were produced using the survey data the case study teams reported, and amended with further observed relationships. Software packages capable of generating sociograms were rejected because they produce lossy projections in which the locations are arbitrarily chosen via an algorithm. Rather, I created the sociograms using Illustrator, beginning with the numerical SNA data and layering on observational data, then evolving location in conversation with the qualitative analysis, such that they represent interactions reported and observed for each team and time. Line thickness represents the strength of the relationship, and color indicates the facet along which the relationship is reported (Changed Understanding, Productive, Progress). Dashed lines show observed rather than reported relationships.

On the sociograms, location is determined based on observed and reported relationships, such as how (independently, in pairs, as a team) subtasks were completed, comments from surveys indicating particular problems or strong relationships, and observations of particular relationships, such as between one team member and a mentor, or observed hostility or socialization between team mates. In some cases, location is literal, as when a one team member consistently stands apart from the others during meetings. The meaning of the locations is therefore explained further in each case. Because these hybrid sociograms incorporate both qualitative and quantitative data, they served as a tool for triangulation, facilitating perspective shifts between the findings from both.

Leveraging These Methods

I have collected data from many sources and across time enabling me to examine various possible relationships and to fully consider the synthesis of my research questions: Innovative design products and process result from social, collaborative team learning in which realistic, ill-structured design problems are negotiated through various strategies and by leveraging various resources and mentors. The methods I employed afforded me the opportunity to triangulate my data and findings. This approach to triangulation through this combination of methods is novel (at least, as evidenced by searching within GoogleScholar for the following search terms collectively: "social network analysis" HLM qualitative triangulation).

SNA has been previously paired with HLM to contrast social networks (van Duijn, van Busschbach, & Snijders, 1999), with qualitative research to locate the boundaries of social groups under study through ethnographic methods (Fleisher, 2005), and has provided representations of qualitative data analysis (Martinez, Dimitriadis, Rubia, Gomez, & de la Fuente, 2003). In other words, it has commonly been used to support one method or another, but not as a bridge *between* methods. As applied in this study, social network analysis facilitated both the more traditional statistical model and the case studies, and in the process, providing a tool for triangulation.

I next present the findings of this study, beginning with the quantitative aspects in Chapter Five, proceeding with the case studies in Chapter Six, and triangulating these findings in Chapter Seven.

CHAPTER FIVE: QUANTITATIVE RESULTS AND MODELS

In this chapter, I first determine whether the trend observed in the pilot study regarding the lack of correlation between Early Efficiency and Final Innovation holds for this study. I then present findings related to the Design Skills test, considering both whether it detected change and how it related to later outcome measures. I then detail the results relating to quantification of interaction as Cohesion, and provide corroborating evidence from correlations within the facets of Cohesion and from an individual measures (CLES) that the social network analysis (SNA) derived measure of Cohesion reflects expected qualities of cohesion. I then explore the usefulness of Cohesion as a variable in this context for explaining variance in interactions and, when combined with Team averages for Design Skills, for explaining variance in Final Innovation and Final Efficiency.

Innovation and Efficiency of Design Products

Expert ratings of design products

The expert ratings of Problem Definitions and Final Designs for Cohorts Two and Three reveal some consistencies. For simplicity, the Problem Definition ratings are henceforth referred to as Early Innovation and Early Efficiency, as these were completed early in the design process. For Cohort Two, Early Efficiency correlates to Final Efficiency; Early Innovation correlates to Final Innovation (Figure 5.1). As was found with Cohort One in the pilot study, there is no significant relationship between Early Efficiency and Final Innovation.

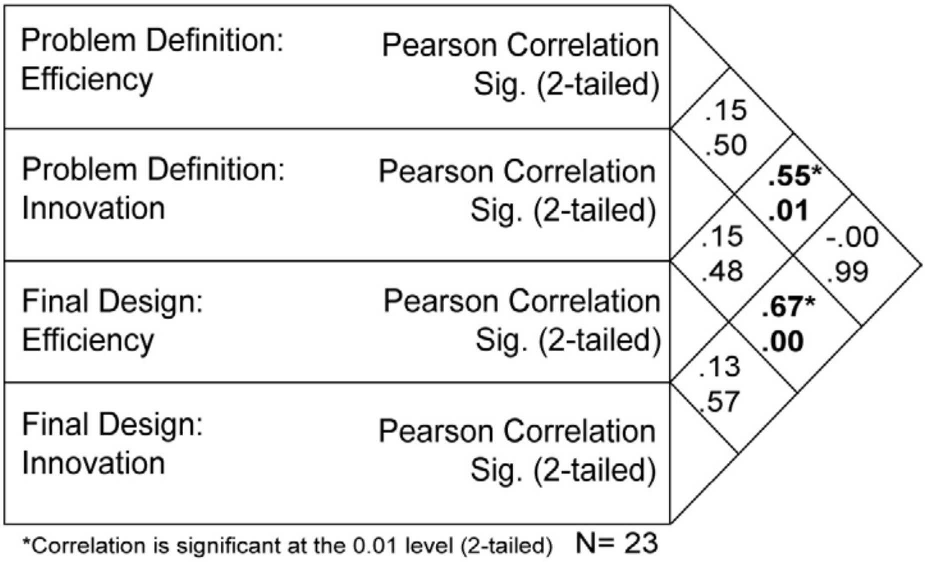

Figure 5.1. Cohort Two Correlations on Expert Scoring

For Cohort Three, Early Efficiency correlates to Early Innovation, meaning that project definitions that were considered innovative also tended to be efficient. This is the strongest correlation observed. As with prior cohorts, Early Efficiency correlates to Final Efficiency; Early Innovation correlates to Final Innovation (Figure 5.2). There is no significant relationship between Early Efficiency and Final Innovation.

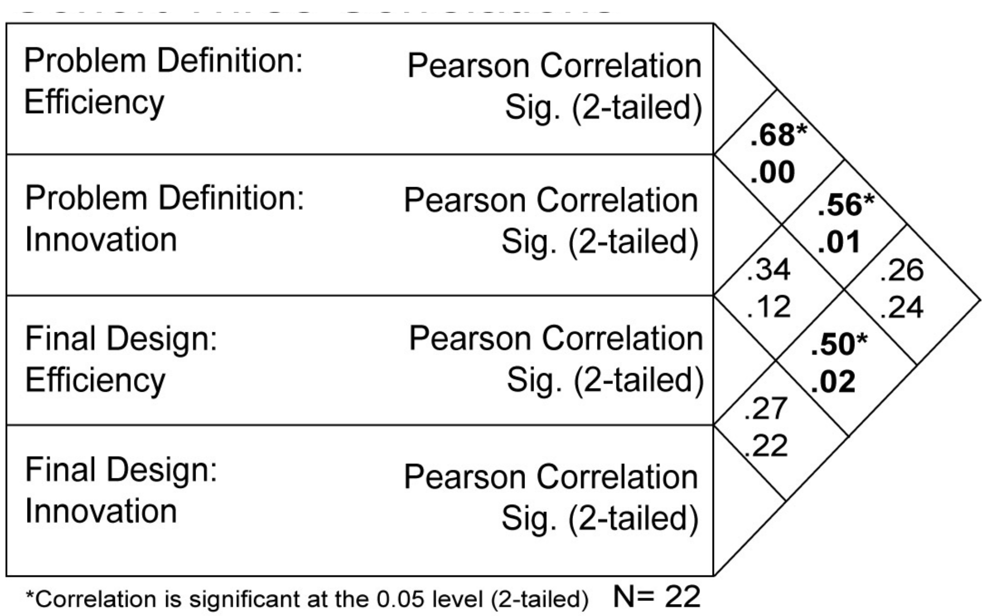

Figure 5.2. Cohort Three Correlations on Expert Scoring

These findings are consistent across cohorts: Early Efficiency does not relate to Final Innovation. Next I explore results from the Design Skills test first considering whether it captured change and then determining whether scores from that instrument relate to any final outcome measures.

Changes in Design Skills

For Cohorts Two and Three most Design Skills increase from the pre-test to the mid-test (Figure 5.3). Teaching assistant and various demographic variables were explored as potential explanatory variables, but none were significant contributors of variance. This finding is interesting because although on some levels the students seem diverse, in terms of commonly used indicators (SAT scores, GPA) they are very similar. A caveat to this finding is that this is the final year of the program; had the same measures been used with first year or sophomore students (a somewhat more diverse sample), it is possible that relationships would be detected. Significant differences were found for two facets: Diagram and Voice of the Customer (VOC); these are explicated next.

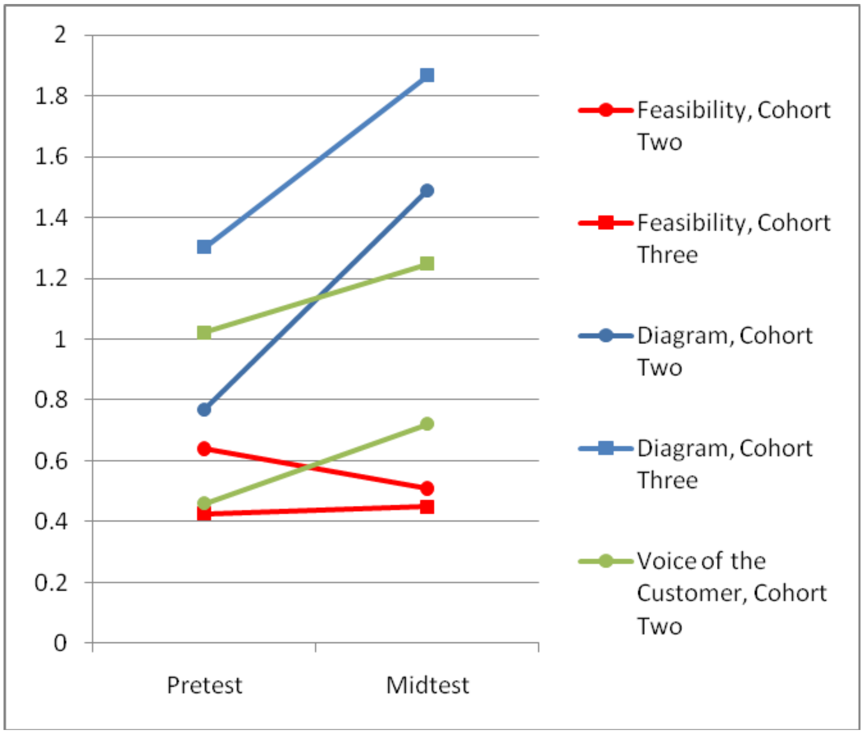

Figure 5.3. Averages on Design Skills for Cohorts Two and Three

Unconditional Hierarchical Linear Model of Diagram Scores on Mid-test

The parameters related to Diagram may be interpreted as follows (Table 5.1): On average, the Diagram score for the mid-test was 1.719. The *t* test result suggests that this score is different from zero (t=17.159, $p < 0.05$).

Student Level Model

Diagram mid-test= $\beta_{0j} + r_{1j}$

Team Level Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

Table 5.1. Unconditional Hierarchical Linear Model for Diagram Mid-test Score

Fixed Effect	**Coefficient**	**SE**	***t* Ratio**	**p value**
Intercept, γ_{00}	1.719	0.100	17.159	0.00
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.003	43	41.557	>0.5
Student level, r_{1j}	1.456			

Conditional Hierarchical Linear Model of Diagram Scores on the Mid-test

The parameters related to Diagram may be interpreted as follows (Table 5.2): The team average Diagram score for the mid-test was 1.428. The *t* test result suggests that this score is different from zero (t=9.096, $p < 0.05$). There is a significant difference between Cohorts (t=2.206, $p < 0.05$). On average, teams score 0.611 points higher than the on the pretest. This increase is significantly different from zero ($t = 2.824$, $p < 0.05$). There is not a significant difference between Cohorts (t=-1.729, $p > 0.05$). The variance of individual scores is 0.012. The statistical test result suggests that scores on Diagram do not differ significantly across teams ($X^2 = 37.934$, $p > 0.05$). Due to a low level two class, the variance may be biased. The intraclass correlation is 0.0091 meaning that 0.9% of variation is due to teams.

Student Level Model

Diagram mid-test = $\beta_{0j} + \beta_{1j}$*(Diagram pre-test) + r_{1j}

Team Level Model

$\beta_{0j} = \gamma_{00} + \gamma_{01}$*(Cohort) + u_{0j}

$\beta_{1j} = \gamma_{10} + \gamma_{11}$*(Cohort) + u_{1j}

Cohort was dummy coded (Cohort 2=0; Cohort 3=1). Diagram pretest scores were team mean centered.

Table 5.2. Conditional Hierarchical Linear Model of Diagram Mid-test Scores

Fixed Effect	**Coefficient**	**SE**	***t* Ratio**	**p value**
Intercept, γ_{00}	1.428	0.157	9.096	0.000
Cohort, γ_{01}	0.437	0.199	2.206	0.034
Pre-test, γ_{10}	0.611	0.216	2.824	0.008
Cohort on Pre-test, γ_{11}	0.251	-1.681	-1.729	0.100
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.012	33	37.934	0.254
Pretest/Midtest slope, u_{1j}	0.017	33	27.839	>0.5
Student level, r_{ij}	1.300			

Unconditional Hierarchical Linear Model of Voice of the Customer on the Mid-test

The parameters related to Voice of the Customer may be interpreted as follows (Table 5.3): On average, the VOC score for the mid-test was 1.028. The *t* test result suggests that this score is different from zero (t=11.803, $p < 0.05$).

Student Level Model

VOC mid-test scores = $\beta_{0j} + r_{ij}$

Team Level Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

Table 5.3. Unconditional Hierarchical Linear Model for VOC Mid-test Scores

Fixed Effect	Coefficient	SE	*t* Ratio	p value
Intercept, γ_{00}	1.028	0.087	11.803	0.00
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.088	43	57.23	0.07
Student level, r_{1j}	0.793			

Conditional Hierarchical Linear Model of Voice of the Customer on the Mid-test

The parameters related to VOC may be interpreted as follows (Table 5.4): The mean score for VOC on the mid-test was 0.712. The *t* test result suggests that this score is different from zero (t=5.825, $p < 0.05$). There is a significant difference between Cohorts on the mid-test (t=3.320, $p > 0.05$). On average, students score 0.240 points higher than on the pretest. This increase is not significantly different from zero ($t = 1.129$, $p > 0.05$). There is not a significant difference between Cohorts on this (t=1.174, $p > 0.05$). The variance of individual scores is 0.075. The statistical test result suggests that scores on VOC differ significantly across students ($X^2 = 63.131$, $p < 0.05$). Due to a low level two class, the variance may be biased. The intraclass correlation is 0.189 meaning that 18.9% of variation is due to teams.

Student Level Model

VOC mid-test = $\beta_{0j} + \beta_{1j}$*(VOC pre-test) + r_{ij}

Team Level Model

$\beta_{0j} = \gamma_{00} + \gamma_{01}$*(Cohort) + u_{0j}

$\beta_{1j} = \gamma_{10} + \gamma_{11}$*(Cohort) + u_{1j}

Cohort was dummy coded (Cohort 2=0; Cohort 3=1). VOC pre-test scores were team mean centered.

Table 5.4. Conditional Hierarchical Linear Model of VOC Mid-test Scores

Fixed Effect	**Coefficient**	**SE**	**t Ratio**	**p value**
Intercept, γ_{00}	0.712	0.122	5.825	0.000
Pre-test, γ_{01}	0.533	0.161	3.320	0.002
Cohort on intercept, γ_{10}	0.240	0.213	1.129	0.266
Cohort on Pre-test, γ_{11}	0.315	0.268	1.174	0.247
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.116	34	63.131	0.002
Pre-test/mid-test slope, u_1	0.260	34	65.172	0.001
Student level, r_{ij}	0.497			

These results demonstrate that although the cohorts score significantly differently at the midtest, their gains on design skills are statistically similar. The initial scores are different as well, and this difference between cohorts on average is maintained. Diagram is the only facet of the Design Skills test on which significant improvement was made. Significant variance remains to be explained in the VOC scores. This facet is of particular interest as it requires multiple perspective taking, a challenging skill to teach yet a critical skill for designers, if they are to allow their designs to flow from diverse customer needs.

Having demonstrated that Design Skills increase, I next focus on Cohort Three in to examine whether Design Skills relate to Innovation and Efficiency. I focus on Cohort Three in particular because for that cohort, I have a greater varietyof measures collected. Given that I am interested in predicting team level measures, I now employ standard regression models with team level variables. Thus, Design Skills are team averages.

The primary outcomes of interest are the expert ratings of Final Innovation and Final Efficiency. I therefore investigated team averages of Design Skills as predictors of these outcomes. I explored pre-test Design Skills, which did not significantly predict Final

Innovation or Final Efficiency. I expected Team Diagram, which reflects conceptual knowledge, or Team Feasibitlity, which reflects factual and practical knowledge, to relate most to Final Efficinecy, and Team VOC, which reflects perspective-taking, to relate most to Final Innovation. Mid-test Feasibility explained some of the variance in the Final Efficiency, but none of the Design Skills explained significant variance in Final Innovation.

Linear Model of Final Efficiency

The parameters related to Final Efficiency may be interpreted as follows (Table 5.5): The mean rating for Final Efficiency was 3.637. The *t* test result suggests that this score is different from zero (t=14.406, $p < 0.05$). Although other Design Skills from both the Pre-test and the Mid-test were examined for correlations, only the Team Average Feasibility score on the Mid-test correlated. A score of one point higher on Team Average Feasibility on the Mid-test corresponds to 1.325 points higher on expert ratings of Final Efficiency. This impact is significant ($t = 2.627$, $p < 0.05$). This correlation is not strong (R^2=0.257).

Team Level Model

$$\text{Final Efficiency}_i = b_0 + b_1(\text{Team Mid-test Feasibility}) + \varepsilon_i$$

Table 5.5. Linear Model of Final Efficiency

	Unstandardized Coefficients		Standardized Coefficients		
	B	SE	β	*t* ratio	p value
Intercept	3.637	0.252		14.406	0
Team Mid-test Feasibility	1.325	0.504	0.506	2.627	0.016

R^2=0.257

Linear Model of Final Innovation

The parameters related to Final Innovation may be interpreted as follows (Table 5.6): The mean rating for Final Innovation was 3.628. The *t* test result suggests that this score is different from zero (t=4.940, $p < 0.05$). None of the Team Average Design Skills from either the Pre-test or the Mid-test predicted significant amounts of variance in Final Innovation. In this model, there is almost no correlation between Team Average Design Skills measured on the Mid-test and Final Innovation (R^2=0.090).

Team Level Model

$$\text{Final Innovation}_i = b_0 + b_1(\text{Team Mid-test Feasibility}) + b_2(\text{Team Mid-test VOC}) + b_3(\text{Team Mid-test Diagram}) + \varepsilon_i$$

Table 5.6. Linear Model of Final Innovation

	Unstandardized Coefficients		Standardized Coefficients	*t*	p
	B	SE	β	ratio	value
Intercept	3.628	0.734		4.940	0.000
Team Mid-test Feasibility	-0.541	0.882	-0.156	-0.614	0.547
Team Mid-test VOC	0.409	0.386	0.274	1.058	0.304
Team Mid-test Diagram	0.178	0.437	0.107	0.407	0.689

R^2=0.090

Summary

The finding that team average initial scores from the Design Skills Pre-test do not predict any outcome scores is compelling because it means that regardless of how they begin, these students have the potential to develop exemplary Innovative and Efficient design. However, it is important to remember that there may be skills not measured that would predict this, and a further caveat relates to the student diversity. Though these students appear quite diverse, on many measures (SAT scores, High School GPA, College GPA) they are extremely homogenous. Still, it is gratifying to see evidence that design process is learned through experience, and not dependent on initial ability in specific pre-existing skills, at least as included and measured here.

The findings related to correlations between expert ratings support pilot research findings demonstrating a lack of connection between Early Efficiency and Final Innovation. Early Innovation correlates to Final Innovation. This tends to suggest the importance of having opportunities to engage in problems with opportunities for innovation. However, experiences during the pilot study led me to question this simple finding; particularly given the diversity in the degree to which teams rely on mentors and upon each other, from case study observations, I determined that it could elucidate more complex relationships by exploring measures of interaction, discussed next.

Measuring Interaction: Cohesion

Plotting facets of interactions (Changed Understanding, Progress, Productive) by mentor role and over time produces varying decay rates (Figure 5.4). What is immediately apparent is that the sponsor is perceived as most important and the TA as least important. Determining the significance of these scores is challenging because the scores are clustered within teams and cross classified. Few teams have the same Faculty Advisor or Sponsor. Additionally, because the changes are relatively small, it is unlikely that they are significant.

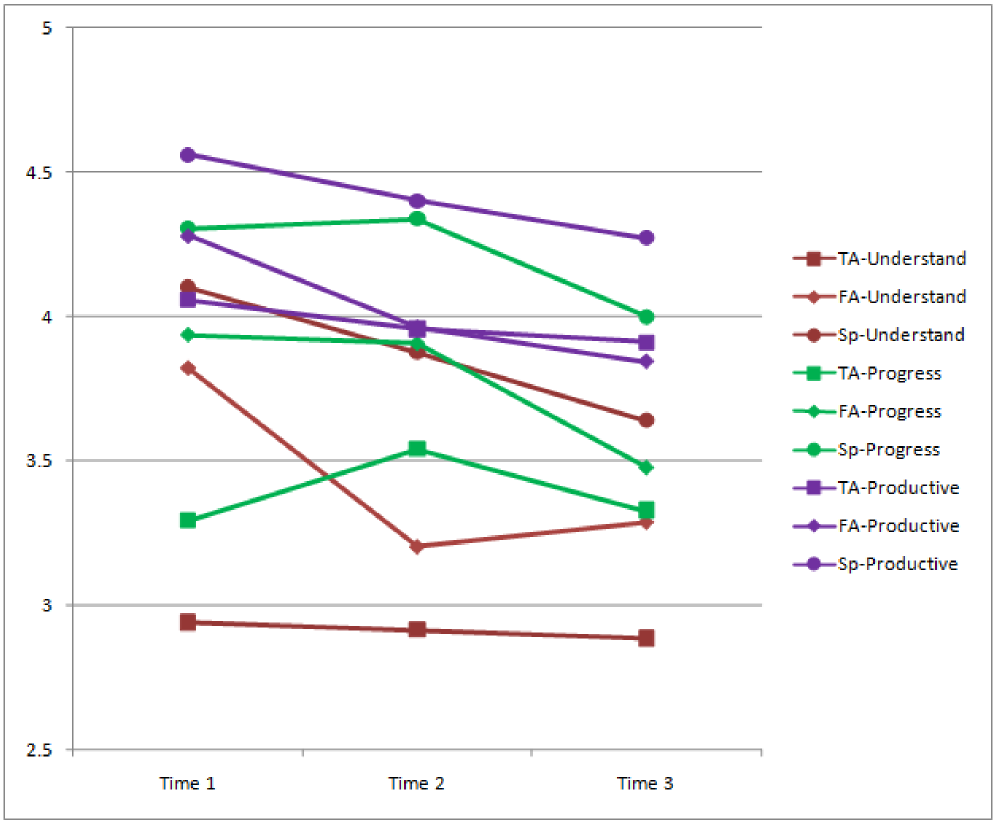

Figure 5.4. *Change over time and across mentors (TA=teaching assistant, FA= Faculty Advisor, Sp=Sponsor) for the three interaction facets: Changed Understanding, Progress, and Productive*

Because of the nature of these data, which describe team members' ratings of the specific interactions, it is possible to produce team level summary statistics to yield a measure of Cohesion for the team, though this is not a simple process. As was described in Chapter Four, a correction factor has been introduced to ensure that all summary statistics occupy a similar space, regardless of missing data due to non-response. Cohesion in a weighted network is a summary of the dispersion of team members' ratings, with lower scores indicating higher cohesion (and lower dispersion of ratings).

By depicting the average Cohesion scores over time, the reduction in dispersion and corresponding increase in Cohesion becomes salient (Figure 5.5). This may describe the development of "teamness." When considered with the decreasing average scores for each mentor, this is perhaps indicative that the teams initially rely more on mentors, but over time, increasingly rely on each other.

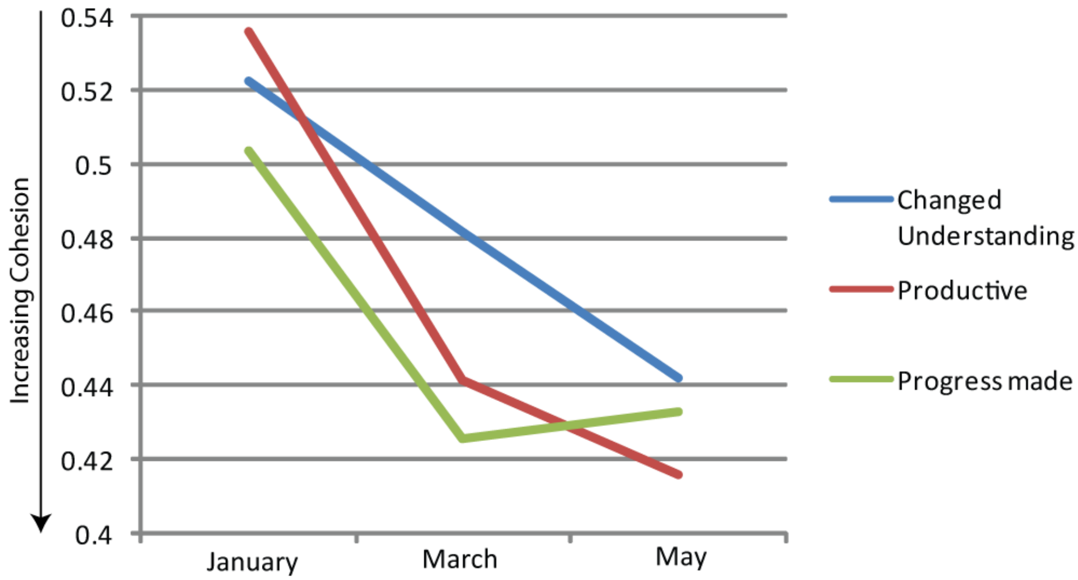

Figure 5.5. Increase in Cohesion over time

These changes over time are not significantly different, though as the sample is low (because this is the number of teams, not the number of students) this is to be expected (Productive, F=2.343, p=0.109; Changed Understanding, F=0.788, p=0.461; Progress, F=0.849, p=0.435). For each case, Mauchly's test of sphericity holds.

Next I consider evidence that this SNA derived measure of Cohesion reflects a more general understanding of cohesion by first considering how facets of Cohesion relate to one another, and then by considering how student level measures relate to Cohesion.

Corroboration of Cohesion

Correlations of facets

Examination of the correlations of facets used to derive Cohesion reveals that scores are highly and positively correlated within time points (Figure 5.6). This finding tends to suggest that this method is picking up a systematic relationship.

Few other correlations can be noted as follows: Progress made, time one correlates negatively with each of Progress made, time three and Productive, time three. This means that higher variance on initial rankings of Progress corresponds to lesser variance in scores for Progress and Productive at the last time point.

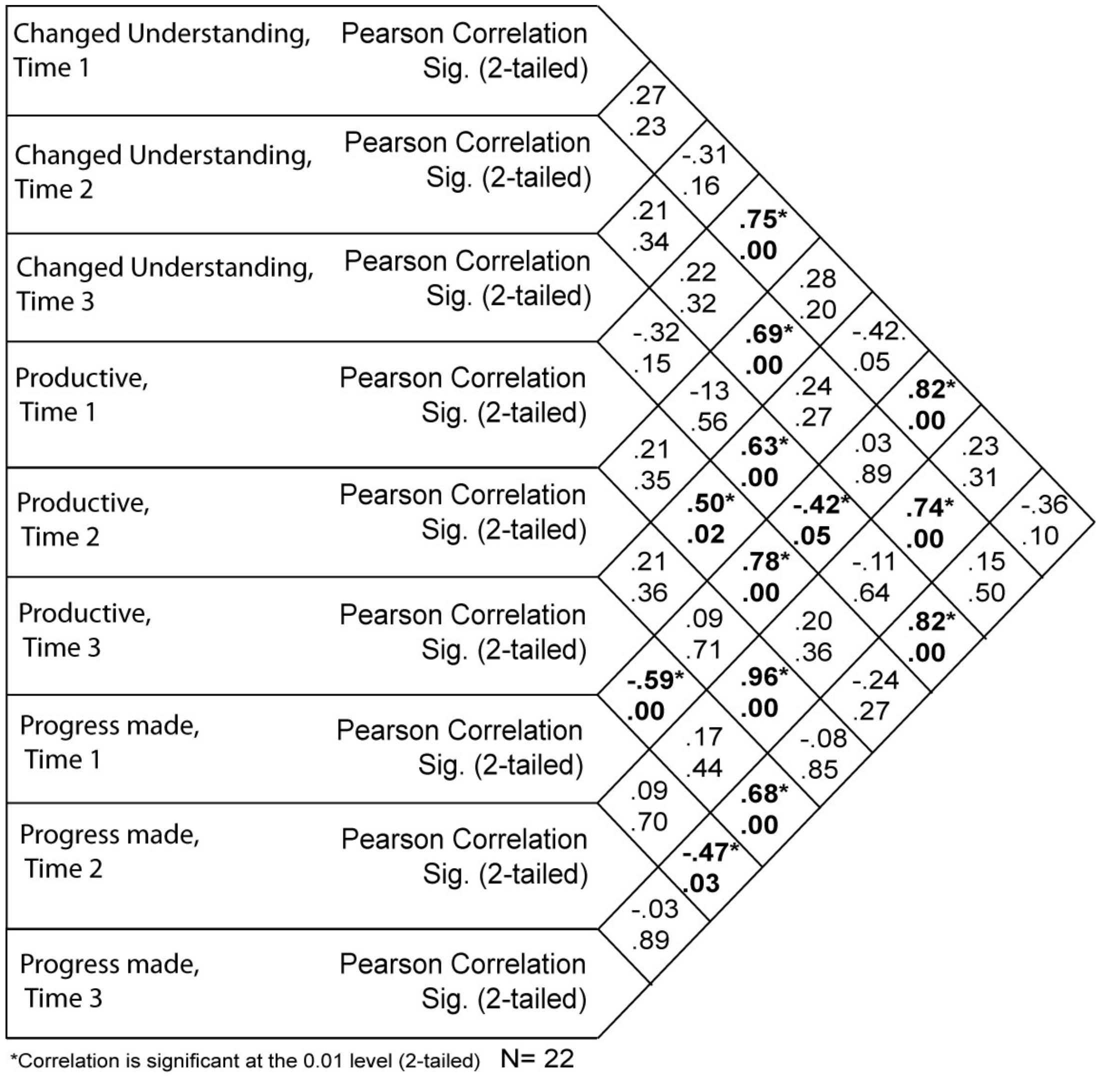

Figure 5.6. Correlations among student ratings of mentors over time and facet of interaction.

Removing the numbers and categorizing the correlations by time and factor provides another way to understand the relationships (Figure 5.7). This representation makes the following salient: Most of the correlations occur within time, rather than within factors. From this, one may infer that there is something systemic and revealed over time, that is, this team level summary statistic describes moments in time rather than the factors themselves.

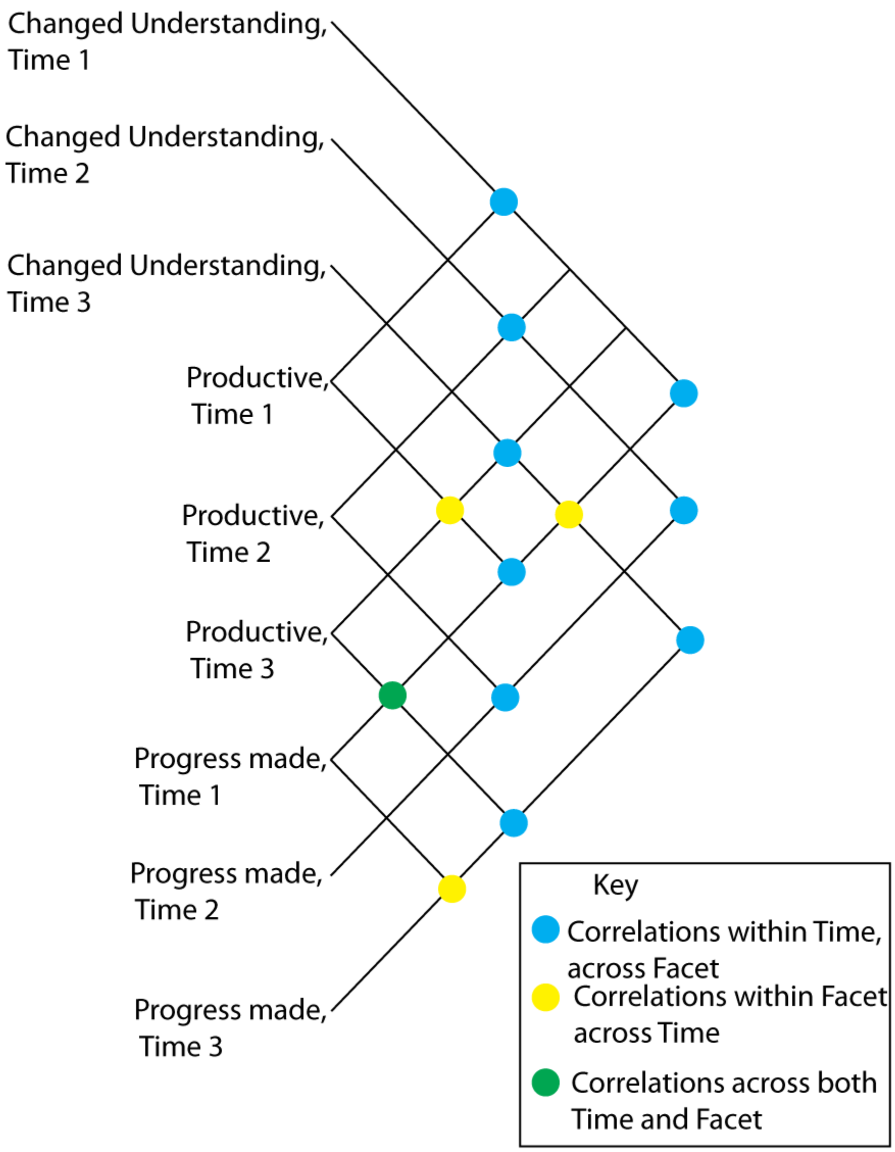

Figure 5.7. Simplified representation of correlations, demonstrating that most are within time but across facet.

Relating to Individual Measures

Although the construct of Cohesion is a field-accepted measure from social network analysis, it has not been much used in studies such as this. Therefore, it would be desirable to determine whether the SNA derived Cohesion scores related to other, similar constructs. Furthermore, given that this is a team level measure, it would be useful to determine whether it relates specifically to individual measures that relate to a more general understanding of cohesion.

Of the individual measures, a facet from the Constructivist Learning Environment Survey (CLES) measuring Student Negotiation is predicted to relate to Cohesion because if students perceive opportunities to compare their ideas with one another, to explain their ideas to one another, their ideas may tend to converge.

Student Negotiation

Student Negotiation is one of the facets from the CLES. Preliminary analysis of the CLES was undertaken as follows: The student ratings from each cohort were examined with factor analysis (Appendix J). Pilot research consistently revealed that the 6th question for the Personal Relevance Scale ("What I learn has nothing to do with life beyond my classroom setting") did not group with any other question, and it was omitted from further surveys. No other questions were omitted as the factors generally held. As implemented, the CLES contained 4 facets believed to be relevant for supporting student learning (Table 5.7).

Table 5.7. Sample Questions from the CLES

Category	Sample Question
Personal Relevance	I learned about the world beyond the classroom setting
Critical Voice	It is acceptable for me to question the way I am being taught
Shared Control	I planned what I was going to learn
Student Negotiation	I asked other students to explain their thoughts

Further preliminary analysis showed that students rated the design class higher than their prior coursework (Figure 5.8). Because students work in teams, a hierarchical model was applied, with Cohort as a team level explanatory variable (Appendix K). Teaching assistant and other demographic variables were explored as potential explanatory variables, but as with the Design Skills, none were significant.

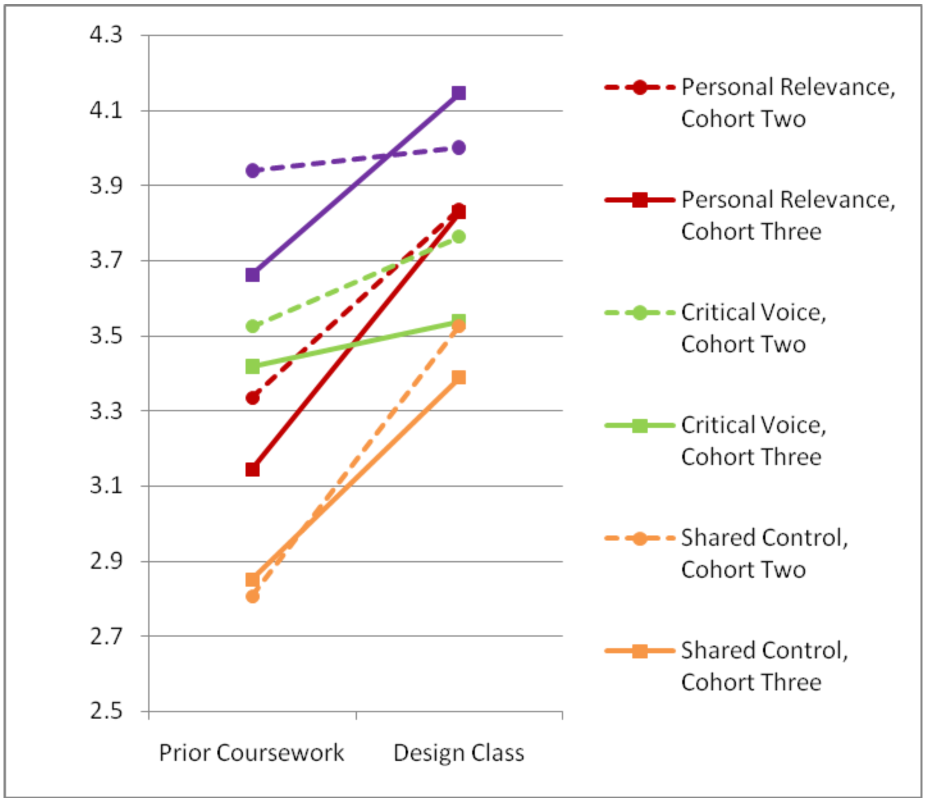

Figure 5.8. Average Scores by Cohort and by facet of the Constructivist Learning Environment Survey

For all factors, the design class is rated, on average, higher than prior coursework, though only the scores for Shared Control are significantly higher. This finding may be attributed to the larger standard errors associated with Cohort Two's scores for the design class. There is no significant difference between cohorts, even for Student Negotiation, for which the trend *appears* to depend on Cohort. For all facets, there is no significant remaining variance to be explained. The results of these tests demonstrate that the Cohorts are more similar than different on this scale, and that the students perceive greater opportunities for planning and deciding how they will learn in the Design course. Student Negotiation, in particular, should relate to Cohesion, explored next.

Conditional Hierarchical Linear Model of Student Negotiation for the Design Class Related to Cohesion

The parameters related to Student Negotiation may be interpreted as follows (Table 5.8): The average team score for Student Negotiation for the Design class was 4.16 given teams with average cohesion and average Early Efficiency. The *t* test result suggests that this score is different from zero (t=54.291, $p < 0.05$). Students score the design class 0.467 points higher than their prior engineering coursework. This difference is significant (t=3.628, $p < 0.05$). Cohesion is a significant factor (t=-1.625, $p > 0.05$). There is no variance remaining across teams for scores on the design test ($X^2 = 13.224$, $p > 0.05$) or in the relationship between the scores ($X^2=10.437$, $p > 0.05$). The intraclass correlation indicates that none of the variance is due to teams.

Student Level Model

Student Negotiation, Design = $\beta_{0j} + \beta_{1j}$*(Prior Student Negotiation) + r_{ij}

Team Level Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

$\beta_{1j} = \gamma_{10} + \gamma_{11}$*(Cohesion) + u_{1j}

Prior Student Negotiation scores were team mean centered. Team level explanatory variables were grand mean centered.

Table 5.8. Conditional Hierarchical Linear Model of Student Negotiation Scores for the Design Class

Fixed Effect	Coefficient	SE	*t* Ratio	p value
Intercept, γ_{00}	4.16	0.077	54.291	0.000
Prior Student Negotiation, γ_{10}	0.467	0.129	3.628	0.002
Cohesion (Facet: Productive, January), γ_{01}	-1.625	0.714	-2.276	0.034
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.000	21	13.224	>0.500
Prior Student Negotiation slope, u_{1j}	0.000	20	10.437	>0.500
Student level, r_{ij}	0.422			

This finding indicates that teams with higher Cohesion would tend to score the Design class significantly higher on Student Negotiation. This finding supports the idea that the SNA derived Cohesion is related to having opportunities to negotiate with others. Next I investigate whether the SNA derived Cohesion scores explain variance in other student level measures.

Relating Cohesion to Expert Ratings

Ultimately, I intended to further explore the relationship between Early Efficiency and Final Innovation, which across Cohorts had no correlation. I considered that an interaction effect could be masking relationships, and that to understand possible pathways through this space would require a more complex model incorporating measures related to interactions with mentors and Cohesion. Because the Sponsor was rated highest generally, in particular highest early in the process, I explored variables related to how students rated their sponsors at this time point.

Unconditional Hierarchical Linear Model of Sponsor Changed Understanding

The parameters related to Sponsor Changed Understanding may be interpreted as follows (Table 5.9): On average, the Changed Understanding score for the sponsor at time 1 was 3.530. The *t* test result suggests that this score is different from zero (t=13.684, $p < 0.05$). The χ^2 test suggests that significant variance across teams remains unexplained (χ^2=43.133, $p < 0.05$).

Student Level Model

Sponsor Changed Understanding = $\beta_{0j} + r_{ij}$

Team Level Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

Table 5.9. Unconditional Hierarchical Linear Model of Sponsor Changed Understanding, January

Fixed Effect	**Coefficient**	**SE**	**t Ratio**	**p value**
Intercept, γ_{00}	3.530	0.258	13.684	0.000
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.738	21	43.133	0.003
Student level, r_{1j}	2.172			

Conditional Hierarchical Linear Model of Sponsor Changed Understanding

The parameters related to Sponsor Changed Understanding may be interpreted as follows (Table 5.10): The Changed Understanding score for the sponsor in January was 3.529, given teams of average Cohesion at the same time who had average Early Efficiency and Innovation. The *t* test result suggests that this score is different from zero (t=16.863, $p < 0.05$). Students in teams rated as having higher Early Efficiency give significantly lower scores for Changed Understanding for Sponsor (t=-1.356, $p < 0.05$).

Students in teams rated as having higher Early Innovation give significantly higher scores for Changed Understanding for Sponsor (t=0.984, $p < 0.05$). Students in more Cohesive teams give significantly higher scores for Changed Understanding for Sponsor (t=-4.244, $p < 0.05$). The results of the χ^2 test suggest that there is no significant variance across teams to be explained ($\chi^2 = 22.104$, $p > 0.05$).

Level-1 Model

Sponsor Changed Understanding = $\beta_{0j} + r_{ij}$

Level-2 Model

$\beta_{0j} = \gamma_{00} + \gamma_{01}$*(Early Efficiency) + γ_{02}*(Early Innovation) + γ_{03}*(Cohesion) + u_{0j}

Table 5.10. Conditional Hierarchical Linear Model of Sponsor Changed Understanding, January

Fixed Effect	**Coefficient**	**SE**	**t Ratio**	**p value**
Intercept, γ_{00}	3.529	0.209	16.863	0.000
Early Efficiency, γ_{01}	-1.356	1.173	-3.023	0.008
Early Innovation, γ_{02}	0.984	0.322	2.427	0.026
Cohesion (Facet: Productive, January), γ_{03}	-4.244	0.262	-3.443	0.003
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.234	18	22.104	0.227
Student level, r_{ij}	2.148			

This model indicates that students rate their sponsor as having changed their understanding of their project when they are in more Cohesive teams (note that Cohesion, by convention, is higher given scores closer to zero, and less Cohesive given scores closer to one) that are rated by experts as having lower Early Efficiency and higher Early

Innovation. This finding is interesting because it demonstrates that incorporating a measure of interaction, (Cohesion), can help explain variance in other measures. Furthermore, this may be interpreted as follows: for teams that were either somewhat underprepared when they met with their sponsors, or that had particularly innovative ideas about their projects, the interaction tended to be particularly impactful for the students.

Relating Cohesion and Design Skills to Outcomes

Next, I explore the outcomes of particular interest: Final Efficiency and Final Innovation. Having established that most individual level measures are not related to these outcomes, and because I have focused primarily on the team as the unit of analysis, I employ standard regression analysis with only team level measures. I include team-averaged variables of previously described student level variables, such as of the Design Skills, and determine whether including Cohesion significantly contributes to models of Final Efficiency and Final Innovation.

Linear Model of Final Efficiency

The parameters related to Model 1 for Final Efficiency may be interpreted as follows (Table 5.11): The rating for Final Efficiency given average Team Mid-test Feasibility was 3.637. The t test result suggests that this score is different from zero (t=14.406, $p < 0.05$). A score of one point higher on Team Feasibility on the Mid-test corresponds to 1.325 points higher on expert ratings of Final Efficiency. This impact is significant ($t = 2.627$, $p < 0.05$). This correlation is not strong (R^2=0.257).

The parameters related to Model 2 for Final Efficiency may be interpreted as follows (Table 5.11): The rating for Final Efficiency given average scores on other measures in the model was 2.951. The t test result suggests that this score is different from zero (t=14.406, $p < 0.05$). A score of one point higher on Team Feasibility on the Mid-test corresponds to 2.011 points higher on expert ratings of Final Efficiency, given average scores on other measures in the model. This impact is significant (t = 5.146, p < 0.05).

A score of one point higher on Early Innovation corresponds to 0.598 points higher on expert ratings of Final Efficiency, given average scores on other measures in the model. This impact is significant (t = 4.805, p < 0.05). A score of one point higher on Cohesion (Late January) corresponds to 1.428 points lower on expert ratings of Final Efficiency, given average scores on other measures in the model. This impact is significant (t = -2.850, p < 0.05). A score of one point higher on Cohesion (Late April) corresponds to 2.187 points lower on expert ratings of Final Efficiency, given average scores on other measures in the model. This impact is significant (t = -2.837, p < 0.05). This correlation is strong (R^2=0.707), and the change in R^2 from model one to model two is significant ($F(4, 17)$=10.245, p<0.05).

Team Level Model 1

$$\text{Final Efficiency}_i = b_0 + b_1(\text{Team Mid-test Feasibility}) + \varepsilon_i$$

Team Level Model 2

$$\text{Final Efficiency}_i = b_0 + b_1(\text{Team Mid-test Feasibility}) + b_2(\text{Early Innovation}) - b_3(\text{Cohesion}_{\text{Early}}) - b_4(\text{Cohesion}_{\text{Late}}) + \varepsilon_i$$

Table 5.11. Linear Model of Final Efficiency

	Unstandardized Coefficients		Standardized Coefficients		
	B	SE	β	*t* ratio	p value
Model 1					
Intercept	3.637	0.252		14.406	0
Team Mid-test Feasibility	1.325	0.504	0.506	2.627	0.016
Model 2					
Intercept	2.951	0.587		5.029	0.000
Team Mid-test Feasibility	2.011	0.391	0.769	5.146	0.000
Early Innovation	0.598	0.124	0.710	4.805	0.000
Cohesion (January, Facet: Progress)	-1.428	0.501	-0.481	-2.850	0.011
Cohesion (Late April, Facet: Productive)	-2.187	0.771	-0.506	-2.837	0.011

Model 1: R^2=0.257; Model 2 R^2=0.707; R^2 change = 0.450

Although other models were explored, Early Efficiency did not satisfactorily explain variance in scores of Final Efficiency, either on its own (R^2=0.302) or with other predictors (R^2=0.311). Cohesion appears to be useful for explaining variance when measured early and late in the project. Cohesion in the middle of the project was not particularly useful in term of explain variance or correlating to other variables. This may reflect the types of activity groups tend to be engaged in across time points in their projects.

Linear Model of Final Innovation

The parameters related to Model 1 for Final Innovation may be interpreted as follows (Table 5.12): The rating for Final Innovation given average scores on other measures in the model was 3.541. The *t* test result suggests that this score is different from zero (t=7.161, $p < 0.05$). No other variables significantly contributed to the model ($t = 5.146$, $p < 0.05$). There is no significant correlation (R^2=0.104).

The parameters related to Model 2 for Final Innovation may be interpreted as follows (Table 5.12): The rating for Final Innovation given average scores on other variables in the model was 1.843. The *t* test result suggests that this score is different from zero (t=2.462, $p < 0.05$). A score of one point higher on Team VOC on the Mid-test corresponds to 0.711 points higher on expert ratings of Final Innovation. This impact is significant ($t = 1.127$, $p < 0.05$). A score of one point higher on Team VOC on the Pre-test corresponds to 0.999 points higher on expert ratings of Final Innovation, given average scores on other measures in the model. This impact is not significant ($t = 2.030$, $p > 0.05$). A score of one point higher on Early Innovation corresponds to 0.672 points higher on expert ratings of Final Innovation, given average scores on other measures in the model. This impact is significant ($t = 3.602$, $p < 0.05$). A score of one point higher on Cohesion (Late April) corresponds to 2.833 points lower on expert ratings of Final Innovation, given average scores on other measures in the model. This impact is significant ($t = -2.530$, $p < 0.05$). This correlation is strong (R^2=0.545), and the change in R^2 from model 1 to model 2 is significant ($F\ (4, 17)=5.098$, $p<0.05$).

Team Level Model 1

$$\text{Final Innovation}_i = b_0 + b_1(\text{Team Mid-test VOC}) + b_2(\text{Team Pre-test VOC}) + \varepsilon_i$$

Team Level Model 2

$$\text{Final Innovation}_i = b_0 + b_1(\text{Team Mid-test VOC}) + b_2(\text{Team Pre-test VOC}) + b_3(\text{Early Innovation}) - b_4(\text{Cohesion}_{\text{Late}}) + \varepsilon_i$$

Table 5.12. Linear Model of Final Innovation

	Unstandardized Coefficients		Standardized Coefficients		
	B	SE	β	*t* ratio	p value
Model 1					
Intercept	3.541	0.495		7.161	0.000
Team Mid -test VOC	0.366	0.325	0.246	1.127	0.274
Team Pre-test VOC	0.544	0.622	0.191	0.875	0.393
Model 2					
Intercept	1.843	0.749		2.462	0.025
Team Mid -test VOC	0.711	0.276	0.477	2.580	0.019
Team Pre-test VOC	0.999	0.492	0.350	2.030	0.058
Early Innovation	0.672	0.187	0.601	3.602	0.002
Cohesion (Late April, Facet: Productive)	-2.833	1.120	-0.493	-2.530	0.022

Model 1: R^2=0.104; Model 2 R^2=0.545; R^2 change = 0.441

Although other models were explored, Early Efficiency did not relate to Final Innovation. VOC was the only Design Skill that explained variance in Final Innovation. As with Final Efficiency, Cohesion in the middle of the project was not particularly useful for explaining variance.

Summary

I have demonstrated that across cohorts, there is no direct relationship between Early Efficiency and Final Innovation. Furthermore Design Skills, on their own, cannot adequately predict Final Innovation and Efficiency. I have explained my method for incorporating a measure of interaction using social network analysis and provided evidence to corroborate its validity as a measure of cohesion. I have built models that demonstrate that the SNA-derived interaction measures of Cohesion explain variance in other variables at the individual level and at the team level.

For instance, students rate their sponsor as having changed their understanding of their project when they are in more Cohesive teams that are rated by experts as having lower Early Efficiency and higher Early Innovation. This may indicate that underprepared or particularly innovative teams tended to have interactions with their sponsors that were particularly impactful.

Additionally, by incorporating Cohesion and Design Skills, I was able to more fully account for Final Efficiency and Final Innovation as follows: Higher scores on Final Efficiency are predicted by higher team scores on Mid-test Feasibility and higher Early Innovation for teams that are more Cohesive early and late in their design processes. Higher scores on Final Innovation are predicted by higher team scores on Voice of the Customer and higher scores on Early Innovation for teams that are more Cohesive late in their design processes.

Both Final outcome scores of Innovation and Efficiency depend on Early Innovation, Mid-test Design Skills, and Cohesion. It is sensible that Efficiency relates to Feasibility, which includes factual and conceptual understanding of the design, whereas Innovation relates to Voice of the Customer, which includes perspective taking.

These findings are also impactful because they highlight the utility of incorporating more process-like measures. If we are to take seriously the idea that learning is fundamentally social, we must find ways to bring interaction into our statistical models; otherwise we misrepresent this negotiated, collaborative process. Next I more closely examine this process by considering three case studies.

CHAPTER SIX: ORIGIN AND NEGOTIATION OF IMPASSES IN DESIGN PROCESS

In order to examine the design process employed by a team, we must look beyond the individual team members and consider the interactions with the various mentors, who may be considered to be part of the extended design team. Each design team is assigned a teaching assistant and sponsor, but the students must seek out a faculty advisor and many seek out additional mentors, either on their own initiative or on the advice of an existing mentor. Although they are not directed to nominate a team leader, one team member is usually designated as such, though this is not always the person who is *functionally* the team leader. Teams and individuals within teams interact differently with their various mentors, and these interactions have direct and indirect impacts on the team's design process and designed product.

Case Study Teams

I provide three case study teams from Cohort Three to highlight challenges students faced in their design teams, and to demonstrate the diversity of interactions with mentors. These narratives follow the teams as they negotiate an impasse. Note that in order to protect the intellectual property of these authentic sponsored projects, specific materials and processes are simplified or renamed. Names have also been changed.

Each case study team is presented as a narrative detailing the life history of the team as an impasse originates and is negotiated. The narratives are extensive, allowing the impasses to unfold in the participants' own voices, and interspersed with interpretation. The narratives are further illustrated with time lines, interpretive graphs derived from social network analysis, and where permissible, photographs taken at various points in the teams' design processes.

Origins of Impasses

Across the case study teams, impasses in design process interrupt forward progress. The impasses are significant barriers that cause the teams to question the feasibility of their projects. The prior coursework of these students focuses on engineering science rather than engineering design. Therefore, when they draw upon past experience, they attempt to leverage their engineering science experiences for understanding their design projects. This framing leads to solutions that are theoretical or situated as engineering science rather than engineering design. This tends to result in a thorough exploration of the conceptual and theoretical space early in the process. Understanding how teams transition towards engineering design perspectives as they negotiate their impasses could further clarify how we might support design learning.

Negotiation of Impasses

The case study teams spend a large percentage of their total project time engaged in problem scoping. This is motivated, across teams, by adoption of theoretical and engineering science perspectives. Though they are encouraged to begin prototyping by their mentors, the teams tend to delay such practical activity because they are burdened by theoretical and engineering science problems.

Whereas the origins of impasses are relatively similar, how teams negotiate and resolve their impasses is more diverse. The following strategies were observed in the case study teams collectively, though not all teams were observed engaging in every strategy:

- Distribution of tasks: Individuals or pairs completed sub-tasks of the project;
- Negotiation of tasks: Team members chose the sub-tasks they worked on;
- Incorporation of Expertise: Team members applied new expertise into their design;

- Help-seeking: Team members sought other mentors, tools, and resources beyond those that were easily accessible;
- Receptivity: Team members were open to new ideas and willing to reconsider previously rejected ideas; and
- Apprenticeship: Team members teach each other.

All case study teams distributed tasks, but not all negotiated how these tasks were distributed. In team 3.3, the leader assigns tasks, whereas in teams 3.2. and 3.4 the teammates negotiate their tasks. Both teams 3.3 and 3.4 engage in help-seeking, but team 3.3 struggles to incorporate expertise. Team 3.2 does not engage in help-seeking, but rather incorporates expertise gained through apprenticeship. The leader for team 3.2 promotes apprenticeship, inviting others into the problem space and being receptive to ideas. By contrast, the leader for team 3.3 excludes his teammates from the problem space and seeks outside experts to help him resolve the impasse. Team 3.2 is the only team commonly observed being receptive to new and previously rejected ideas.

Teams 3.2 and 3.4 are driven to prototype by the approach of the end of the semester, and this in turn leads them towards a final design solution path. Consequently they do not have time to iterate on their final designs. Prototyping shifts their perspectives from theoretical and engineering science to practical and engineering design. This framing is crucial, as some theoretical engineering problems are not problems in practice, due to their transient nature.

These assertions are warranted by the narratives, which unfold next, punctuated by my interpretations. I follow the narratives with cross case analysis and revisit the origins and negotiation of impasses within these student team design processes.

Team 3.2

Team 3.2 is a four member team with four native English speakers: Cynthia, a Caucasian woman, Greg, Tom, and Addai, all Caucasian men. Tom is their team leader, and manages the team with grace. Their teaching assistant is Shanti, a South Asian woman. Their sponsor is a physical therapist from a local hospital, and their faculty advisor is a biomedical engineering professor. In addition to the sponsor, they commonly interact with another man from the hospital. Their project involves designing an innovative tool to be used by physical therapists for measuring motions in patients' limbs.

The team members are welcoming to me, and make an effort to explain their project and weekly progress to me. Tom, in particular, is masterful at explaining the complexity of the wiring in their device. This attribute is patently visible in his leadership; he frequently checks with his teammates to make sure, when discussing something complex, that they are engaged with the conversation and invites their explanations and questions.

The device team 3.2 is designing needs to monitor changes in applied pressure during motion. They have selected a sensor for recording changes in pressure and an accelerometer to record motion, however, including this is nontrivial: the accelerometer itself will rotate through space, and this proves to be challenging for them to understand and functionally incorporate into their design.

Though Tom explains that he suspected this problem would occur as early as December, it does not operate as an impasse directing the team narrative until more than three months into the sponsored project (Figure 6.1). This impasse proves to be lingering and recurrent, taking many months to resolve, and their negotiation of it is populated by several false starts at possible solutions.

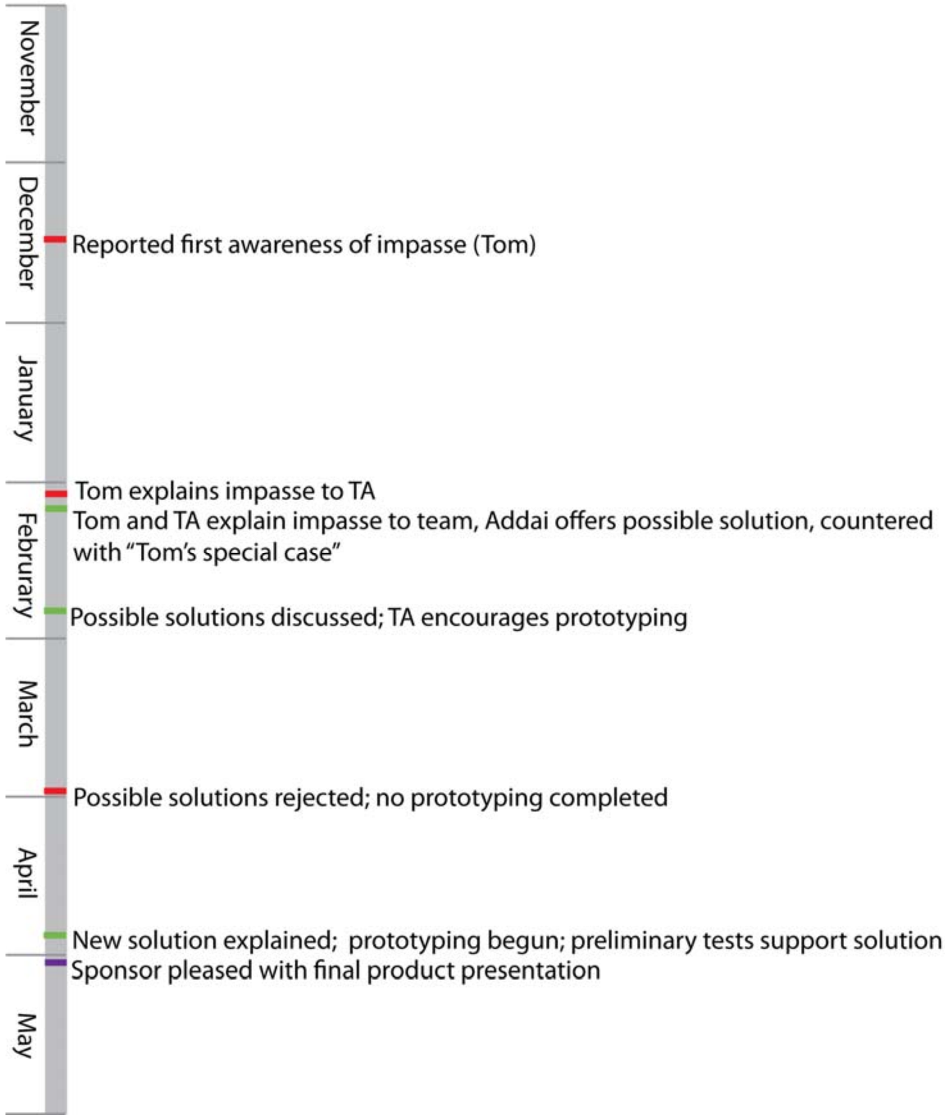

Figure 6.1. Timeline for Team 3.2

Themes

Various themes that emerge from the team narratives. These focus on understanding what prompts the impasse and why it exists as an impasse, as well as how the team seeks out mentorship and resources and makes use of mentor expertise. These themes will be considered throughout the narratives and are contrasted in cross case analysis as well as in triangulation of the overall findings.

Origins of an Impasse: Science and Engineering Goals

I posit that this impasse exists and maintains a hold on the team largely because science/theoretical perspectives have been privileged over design/practical perspectives. The cases in which the impasse (which will become typified by “Tom’s special case”) would occur in practice prove to be so rare and transient that it is not even an issue, but recognizing that it could occur holds up development of the design. The TA pushes the team to test, to try. This narrative highlights a difference between science and engineering, because the design solution - essentially ignoring this problem - would not be appropriate had the goal been to perfectly document motion and force, but given the goal- to approximate changes in force at relative times in an interval, the problem becomes relatively unimportant.

Strategies for Negotiating an Impasse: Creating and Maintaining Shared Problem Space

Tom, as we will see, invites collaborators into the problem space. He instantiates an apprenticeship model for his team, initially explaining the problem to the TA and to me, then to his team mates. Each of these conversations is effortful and time consuming but all team members can explain why this is challenging and all team members feel they have learned something. Tom can think in vectors, and this means he has to translate his thinking to Cartesian space, using his body to demonstrate first vectors then actual motions. This case study team, though they distribute and negotiate tasks, engage in apprenticeship, teaching each other enough about their tasks such that they understand how their tasks interrelate. They are adept at incorporating the expertise resultant from interactions with their mentors and each other, though they do not seek out other mentors or outside resources beyond what is expected, and make little use even of their faculty adviser.

Another aspect of maintaining shared problem space, and one that is somewhat unique amongst the case studies is receptivity to new ideas and to old ideas reconsidered. Rather than rejecting an idea out of hand, Tom and the TA both encourage consideration of possible solutions, engaging in thought experiments (one of which results in the exemplar, “Tom’s special case”) to consider the possible consequences of design directions.

Team 3.2 and “Tom’s Special Case”

Tom, the team leader, is initially the only one aware of the problem the accelerometer presents. He invites others, even me, into the space by making sure everyone understands the problem. This impasse is a recurrent issue, first presented by Tom to Shanti, the teaching assistant on February 4th, 2008 towards the end of the weekly meeting. At this point his team mates don’t understand and this initial conversation is essentially between Tom and Shanti. Discussion of the accelerometer problem begins as Shanti asks how many accelerometers will be used, and probes to understand how the accelerometer functions. As Tom answers her questions, he brings up the accelerometer problem, of which he has been aware for some time.

Tom: You put it on a flat surface and calibrate each side, um, you'll be able to, in an arbitrary location, if you hold your hand still, you'll be able to tell which way is down, like it will, you'll know which orientation your hand is in, so ... um, one, uh, this is actually a problem in our design the fact that the gravitational field will register here.

Shanti: Right.

Tom: Because as we rotate around, this large acceleration is gonna drift across our coordinate plane.

He also has a potential solution to this issue, though he explains limitations to this solution:

Tom: And so what we need to do is we have to develop the assumption that, um, the hand is gonna have two orientations to start and to finish-

Shanti: Uh-huh.

Tom: -orientation, and we're gonna have to assume that the glove is going to make a smooth transition between them but, uh, [laughs] this is where it's tricky, uh, the components of, if, if we were in a micro gravity, um, situation where gravitational field wouldn't affect the sensors.

Shanti: Right.

Tom: Um, only as you move it, you would get like, um, if you move while rotating your arm, if you moved it while keeping your hand in the same orientation, and you just moved in one direction.

Shanti: Mmhmm.

Tom: That X and the Y would both just be flat lines and the Z would have, like, a positive acceleration and then a negative acceleration and then it would be back to zero...right. You understand?

Shanti: Right.

Tom: Uh, as you, if you were to do it while rotating your arm- all that's gonna happen in some respect on every physiological movement- you're gonna be rotating your arm over, turning your wrist, um, you'll get components of that will be in the X, Y, and the Z.

Shanti: Mhmm.

Tom: It will sort of go from one to the next to the next as you rotate your arm while moving in the same direction. […] At the start of the range, your hand's not gonna move or it's gonna move negatively- just flutter around a small amount. The largest component of it will be gravitational field, so we'll know from that. From that, we'll estimate our starting orientation, at the end of the range your hand will also be still, so it, the first few samples will be at the beginning orientation and the last few samples will be at the end of orientation and we'll be able to estimate our final position, and so we should be able to, in theory, um, just interpolate in between. […] That's my plan right now. I don't know if it's gonna work. […] Does that sound reasonable to you? At least a first order approximation? […] We knew gravitational fields would mess up this algorithm, uh, early on and this has sort of been on the back of my mind and it wasn't till actually after our proposal and sort… or over Christmas break that I started thinking of how much of a problem this is gonna be 'cause I have a feeling this gravitational field problem will be pretty strong or not negligible.

This passage highlights Tom's understanding of this problem as a theoretical obstacle. The reason he fears it will not work is because of his understanding of the theoretical aspects. Tom has been anticipating it as a problem, but cannot estimate to what degree ("pretty strong or not negligible") it will impede their design because he lacks practical experience.

The problem is challenging to understand as it requires integrating knowledge of gravity, acceleration, and rotational fields. As Tom explains, Shanti's responses are hesitant and as Tom persists in his explanation, Shanti indicates that she does not see why it is a problem ("I don't get it, why should it be along Y") and Tom repeats his explanation again, but this time illustrating the problem with hand motions to show how the device would move through space, and at what point he predicts a problem would occur. This gesture-rich explanation allows Shanti to see the problem space (": I see, cause now you don't know what your origin is or what your direction of the gravitation is."), though she does not yet explore it with him:

Tom continues to explain how this problem will impact them and how they might deal with it, though he warns, only as a "first order approximation." He cautions Shanti that "It's not gonna be fantastic." Shanti encourages him to try it out to see how much of a problem it will actually be:

Shanti: Yeah you need to like try [inaudible]. Do some sort of experiments where you turn the sensor all possible directions plus angles, um, and see what signals you get. That's gonna be a baseline without the hand. That might be one way to do it.

This practical suggestion is not taken up for many weeks. Rather, the team perseverates on what is, at this point, a theoretical issue, conducting thought experiments but no actual experiments. This is an example of how theoretical perspectives are privileged over design perspectives. This may result from the focus on engineering science and analysis that takes up much of their prior coursework.

This exchange also highlights how committed Tom is to bringing others into the problem space with him. He patiently explains, and then when he realizes that his explanation has not been understood, he changes his explanation, using gestures to create a joint problem space.

The team interactions at this point in the team's life history are represented by lines of varying thickness and color on a hybrid sociogram (Figure 6.2). Tom and Greg are observed to work closely, and Tom is the one who most frequently primarily speaks to the TA. The sponsor is located towards the bottom of the sociogram because the role the sponsor plays is very much a bottom-up role. Though the sponsor has created this project, he has not constrained the team much in how they should proceed, in part because of the exploratory nature of the project, but also because the sponsor lacks the expertise to design the device. Whereas in some teams, the sponsor uses the team as a means to explore a question that would be expensive to assign to a professional team or as a way to develop part of a larger project, in this case, the team must provide the expertise and even teach the sponsor some of the content in order to understand the device.

Note that Cynthia is located closer to the sponsor and further from the rest of her team mates. This location represents both her responses to surveys indicating that she feels she has less to contribute and her posture at team meetings; she often physically positions herself slightly outside the team. Additionally, she, of all the team, most often mentions the sponsor. It is worth noting that her team mates do not report that she contributed less to the team; it seems that she sees less value in her contributions. The location of the faculty advisor reflects the relatively unimportant role he plays, especially in terms of the impasse; in fact, Tom does not even attend meetings with the faculty advisor. This team does not rely much on outside mentors either.

Another thing to notice in this sociogram is that the lines are of nearly equal thickness, indicating that the students give similar scores and are therefore fairly cohesive, particularly for Cohesion ratings derived from Progress and Productive.

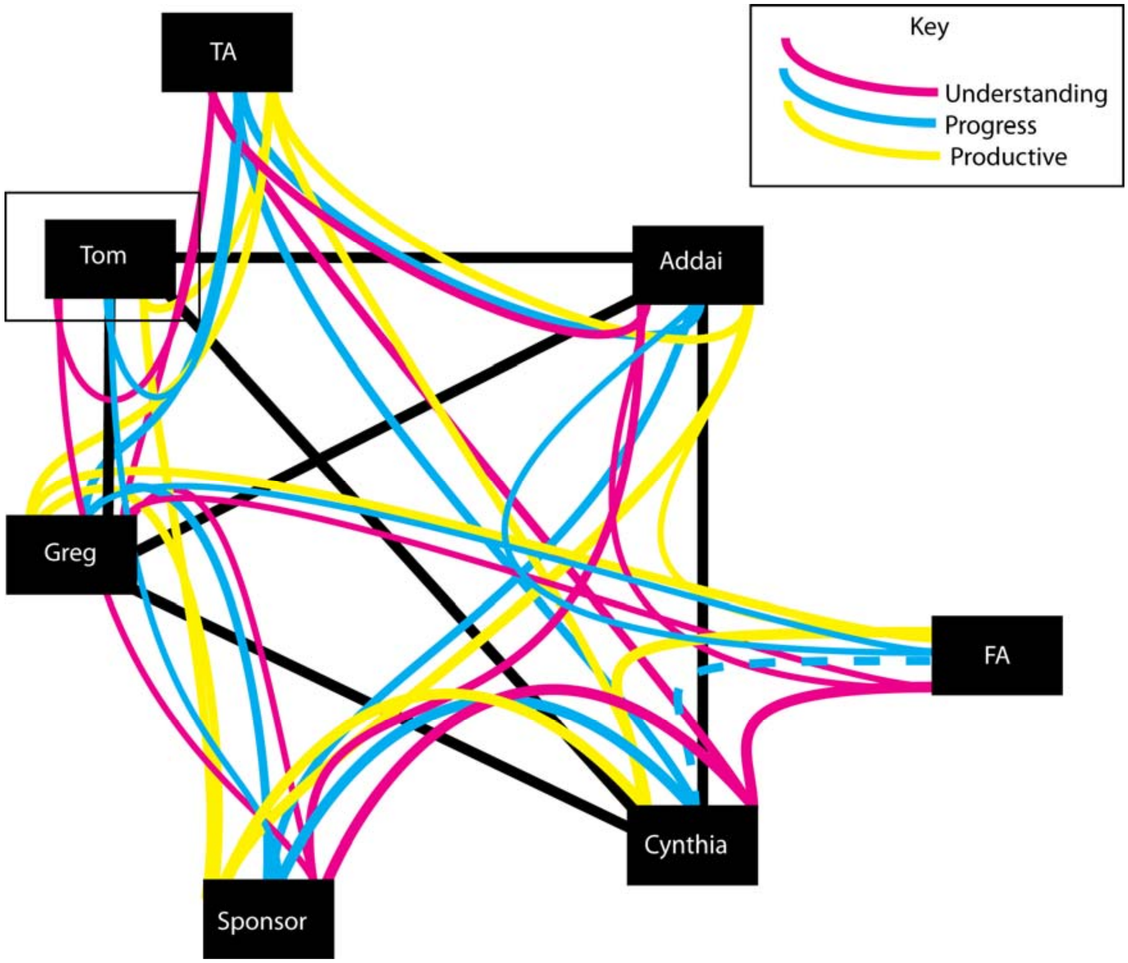

Figure 6.2. Hybrid sociogram of Team 3.2 early in the project

One week later, on February 11th, Tom presents the problem of the accelerometer to his team mates, now assisted by their TA. At this meeting, everyone really gets into the discussion. They use lots of gestures, they draw their ideas, they pose questions, and use their bodies to create a shared problem space. Though there has been conversation within the team previously about this problem, Tom and, to a lesser extent, Greg and Shanti are the only ones who understand why it is a problem.

Tom introduces the topic by exploring a possible solution: they have ordered an inclinometer, which Tom hopes "will provide complementary data to the accelerometer," though they are not sure how it functions and are therefore not sure it will solve their problem. Tom briefly explains the problem, but Addai remains unconvinced, and they discuss the problem further:

Tom: It would be able to tell us our initial and ending orientation and actually all the orientation throughout the measurement so if we could- the idea is to correlate, um, the data such that whichever direction the inclinometer tells us is gravity, we subtract one gravity's worth of acceleration from the accelerometer reading so that's always canceling out the effects due to gravity.
Addai: Have we-? I talked with Greg a little bit about that and I guess I'm not completely sold this gravity is going to be an issue until we start talking about…
Tom: Okay.
Addai: Are you fully confident in the fact that it will be?
Tom: Fairly certain it will mess us up to some degree, I just don't know how much. I know it will mess up the readings if we don't correct for it at all, um, I don't know how much.

Addai asks Tom if "this been addressed in the literature?" and Tom mentions some applications of accelerometers, but Shanti points out that these are not relevant for understanding their problem. This is the first time she has actively participated in the problem space, and is evidence that she does now understand why it is a problem. However. Addai remains peripheral:

Addai: How realistic do you think this scenario is?
Tom: Like relying entirely on it.
Addai: We're relying heavily?
Tom: Heavily on? Um it's hard to say at this point, really don't know what the sort of noise and things we're getting from the accelerometer.
Addai: Okay, but you still think we'll be able to get, uh, velocity data?
Tom: I think so, […] however, any error in your acceleration channel will propagate as you get worse and worse, so you get farther and farther from the true value if the error isn't, um, evenly distributed about zero.

Tom explains code he has written that may address this, but Addai is still trying to figure out why it is a problem:

Addai: Forgive my ignorance but, uh, so you got an accelerometer?
Tom: Yeah.
Addai: Right, and the way the accelerometer works is it has some sort of, um [inaudible] goes in all three dimensions?
Tom: Yeah.
Addai: And as you move, your little bead or little pendulum will shift in one direction or the opposite direction of movement?
Tom: That's right.
Addai: So it uses that potential to calculate?
Tom: That's right.

He understands the mechanics of how the device functions, but does not see why their application of the device creates an unusual problem:

Addai: Why do you need to correct for gravity? […] I know the limb you're trying to move is being affected by that same g force your hand is being affected by that g force, so why does that affect the use of the device?
Tom: The output of the accelerometer is, uh, a measure both gravitational field and, um, movement contributions.
Addai: Okay?
Tom: So when you- if you hold your hand in plane- still - for, like you said half a second, um, the X and Y channels that are reading zero, and the Z channel is going to read negative one or positive one or whatever, um, as you shake it around it's gonna- all three channels are gonna receive the sort of motion-dependent contribution superimposed with gravity, so gravity will always be affecting it in the downward direction so as you move it around, the Z channel will basically have all the motion shake lines superimposed on top of the base line.

Addai demonstrates that he understands part, but not all, of the problem. He is also adopting a design perspective by reframing the problem. He suggests that they make a compromise, such that they will get less information, but perhaps enough. Shanti encourages this line of designerly thought experiments:

Addai: Instead of taking measurements in three dimensions, this is like maybe a first draft, you throw away the position information and we roll the XYZ coordinates into one combined vector and that way we've always accounted for your full gravitational contribution.

Shanti: That's a good idea!
Cynthia: Yeah.
Shanti: Like a magnitude.
Addai: So you roll them all together.
Shanti: That's a good idea. […]
Addai: I mean, you'll lose your position but you'll probably get a very, a standardized, you'll get for sure a very standardized acceleration, and you're gonna figure out velocity.

Tom has previously considered and rejected this idea because it does not provide an answer to the theoretical problem, yet he is receptive to the idea and entertains it within the team to a full extent. He leverages Addai's idea to bring everyone else into the problem space that he has constructed. He draws on a piece of paper to clarify ideas, but he sees the problem as best understood from vector space:

Tom: So you're saying, say, yeah, hold it still and um, gravity's looking like this and it has a magnitude of like, one g so later I move it about and I get some arbitrary [Draws XYZ, vectors] vector here...

Once he has drawn a representation of the problem in vectors (Figure 6.3), he begins to frame the accelerometer problem by asking them to consider a specific situation, which will later be referred back to by the team as "Tom's special case."

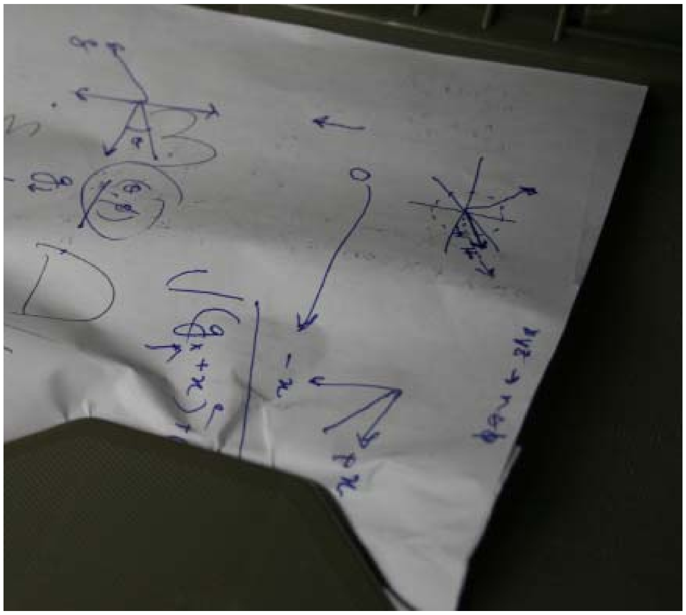

Figure 6.3. One of the pieces of paper used as the team explored their understanding of the impasse

Before letting the team explore this option, he returns to his earlier possible solution of incorporating another device, an inclinometer. Shanti sees this as evidence that he has not understood Addai's suggestion and restates it:

Shanti: What Addai is suggesting is that, like, when you rotate it, um, the direction g is gonna maybe split out along the two dimensions.
Tom: Right.
Shanti: But if you took the magnitude would it sum to the same? Is that what you're saying?
Addai: What I'm saying is you don't even care about it. What I'm saying is you don't even care about subtracting it.
Shanti: Yeah.
Addai: Because we're looking again at a real world relativistic type change and so let's say this change this is your first position data, okay? We know that there is a gravitational component.
Tom: Mmhmm.
Addai: And we know that it's in this example [pointing to Tom's vector example] going to be one in the Y direction and you could figure out the magnitude of this vector

if you sub- like, alright, you're gonna have like ninety degrees coming in Y and like zero degree- zero degrees everywhere else.

Shanti engages with this possible solution by writing out the equations they would need to use. She explains the math they would use to do this. She checks in multiple times with Tom to see if he understands and he affirms that he does.

Addai's solution is a solution to "a real world relativistic" problem, as he describes it, whereas the problem Tom is trying to solve is theoretical and has a greater focus on understanding and predicting the outcome before trying. Addai expresses hesitancy about his solution as a good solution to a real world problem. Shanti again checks in with Tom and affirms Addai's idea:

Addai: I mean, I'm still not sold on it, but I'm not sold on it, but I like the way it looks. […] You lose your position [inaudible] but it would be a much easier way to keep track of your overall change in, uh, applied force velocity.
Shanti: Yeah.
Addai: Cause you don't have to track it in three dimensions anymore. […]
Shanti: But it's good.
Tom: Yeah I agree with all this.
Shanti: Addai- he's having his moment of glory. [giggles]
Addai: Good old high school physics, you're useful for something after all.

However, Addai then tries to get back what was lost in the earlier compromise (this is perhaps attributable to the shift between vector and Cartesian space). Shanti entertains this idea with him:

Addai: Going back to this method, do you actually lose the position data? Because the, the new vector you made still exists in three dimensional space? […]
Shanti: You're just getting the length of this vector that connects your origin to that point- all you're getting out.
Addai: You just get magnitude?
Shanti: [leaning down and drawing] You just get the magnitude. So it's kinda like if you have three dimensional space and you're sort of tracing out using a vector, uh, if you could somehow get this angle as well, the azimuth and the elevation then you

could actually get everything, then you have it. Do you see what I mean? [Directed to Tom]

Tom: Yep.

Addai: What stops us from getting the angle?

Shanti: Nothing. We're still getting XYZ right.

Tom questions her on this and she moves her explanation to Tom's drawing which is in vector space. Tom highlights the ambiguity they will deal with and moves the thought experiment back into the theoretical realm:

Shanti: You're basically on a sphere here and this r is always going to be g.

Tom: Correct.

Shanti; Yeah?

Tom: I agree.

Shanti: And if there is something applied, then you're either gonna go inside the sphere or outside the sphere?

Tom: I agree, but you don't know. What I'm saying at any arbitrary point we don't know. Say you're in the middle of your data, right? So X, Y, and Z is just an array, an infinite array. So just pick some arbitrary X, Y, and Z acceleration.

Shanti: Okay. […]

Tom: How do you know that-? What if gravity was in this direction? Then you know you're moving, accelerating downward at this distance, this difference right? You're accelerating downward slightly faster than gravity, but what if gravity was at this point this way then you know you're moving up and left but what if gravity was coming out of the board? Then you know you're moving up and right. See what I mean?

Shanti: No, I didn't get.

Tom: You don't know, I mean if you just collapse the concept of gravity into a magnitude and not a direction, it leaves your acceleration ambiguous.

Shanti: Okay?

Tom: Becau-, you lose all of your angle information. So you get a magnitude but even, it does worse than that! You don't- you've lost your angle information if you just collapse it to a magnitude.

Shanti: Mmhm.

Tom: Right, cause you don't know which way gravity is facing because we're at some arbitrary orientation, um, um, if you don't, so, saying, if this is in conjunction with the inclinometer, so we would know which dir-. We have to know which way gravity is facing, so if the inclinometer can tell us that at all times which direction gravity is, we can subtract one from it and get- you know you can compensate for gravity and get your motion component- what we need.

Tom next introduces the problematic example, later known as “Tom’s special case,” drawing and gesturing, but it is not taken up initially, in part because he does not yet specifically isolate the problematic aspect which only Tom sees as apparent, in part because he keeps it in theoretical/vector space initially:

Tom: Say this direction is gravity. We have a limb. This is someone's arm and it’s gonna go this way so I'm gonna push someone's arm orthogonal to gravity.
Shanti: Okay.
Tom: So the test starts.
Shanti: Okay.
Tom: My hand is still.
Shanti: Right.
Tom: I'm gonna get a gravitational thing which is pushing down.
Shanti: Right. [Tom demonstrates this with his arms, Shanti takes up his gesture]
Tom: In the middle of the test I'm pushing forward so gravity is going to do this. It’s gonna be a combination of this plus the direction I'm pushing, right?

Addai decides the best way to deal with this is to continue to sum the vectors, but not subtract gravity. Shanti encourages them to transition from thought experiments to actual prototyping, and Tom picks up on the need to address the problem from a design rather than theoretical perspective:

Addai: I think it might do us more harm than good if we try and factor out gravity.
Shanti: I don't know. I think you should just try it. I think you should try. I think this is a very simple approach so I would say that try this first.
Tom: A first order approach, yeah and again, we're uh, I guess I, what I was losing sight of was I was everything we are doing now is a first order approach and then continue thinking about the details.

But then, after a brief pause, Shanti really takes up the accelerometer problem, and Tom is able to reintroduce his “special case” more clearly:

Shanti: The one thing that [?] is that it, there might be a situation where say you are at a certain angle and then gravity splits along-
Tom: Yeah.
Shanti: -along certain components-
Tom: Okay.
Shanti: -and then what happens is that, what happens if you add it to this component, and you subtract it from this component does it cancel out in the magnitude?
Tom: As far as movement?
Shanti: Yeah, do you see what I mean?
Tom: And that's what I was talking about here. […] You may push in such a way where you move along the sphere. [Note that this would equate to actual motion appearing to be zero motion]
Shanti: Do you see what I mean? Yeah. Yeah, I see what you mean. […]
Tom: So you'll get errors if you don't know the direction and so this is only the most obvious case where you'll move along-
Shanti: Along the sphere.
Tom: -sphere and you'll get no change, that's the easiest to see, it's the easiest to see the error because you're moving and not reading it.

That Tom considers this an "obvious case" highlights his relative ease within this theoretical space. Addai enters the exchange but has trouble "seeing the vectors." He uses the word movement, for instance, rather than acceleration. When Tom presents his special case in terms of vector space, Addai interprets it in Cartesian space, and in doing so cannot see why it is a problem. Shanti also joins Addai's explanation as she defines what the surface of the sphere represents:

Addai: Once you start adding movement in any direction.
Shanti: Acceleration.
Addai: Acceleration.
Shanti: Right.
Addai: Then you leave the plane of the sphere, the surface of the sphere.
Tom: Unless you move in such a way where you move along it. […] There are movements you can take that will keep you on the sphere and change your angle only. […] Well, that's easy, so okay, so, say these just, um, initially pointed straight down. It's at level one, right? If you wanted to move up here all on the

other side, all you'll have to do is move one g up to cancel out g - to cancel out g and then one g left to cancel out g and then you'll be on that sphere.

While in vector space this describes the components of one motion, interpreted in Cartesian space, this same explanation appears to describe a series of movements, and this is how Addai interprets it.

Addai: Right, but then you won't be moving any more, which is what we want. When you're doing the movements you've left the surface […] but while you're doing the movement you've left the surface.
Shanti: Yeah.
Addai: Inside or outside the circle. When you're doing the movement itself you've got either more or less than one g.
Shanti: Exactly. That's how you're moving otherwise you're not moving if you're on the sphere, there's only g acting on it. I agree, so you're gonna go off the surface and come back to the surface. So yeah, I agree. [she laughs]

While this is an accurate interpretation in Cartesian space, it is not the case Tom intended. Tom reframes his special case, moving it out of vector space into Cartesian space, and gesturing to demonstrate the case he wants them to consider. This shift from theoretical to actual is critical for design, but this "special case" is essentially an exemplar of a theoretical issue and once apprehended, will haunt the team.

Tom also simplifies the "special case," isolating the problematic aspect, and when Shanti and Addai have understood that, he makes it more complex, and finally Shanti and Addai fully see the problem of the accelerometer through "Tom's special case":

Tom: So what if you moved downward only at g? […]
Addai: The upward magnitude, it'll sum to zero. You'll be in the center of the circle.
Shanti: Yeah.
Tom: So what if, what if you do that and at the same time you accelerate leftwards at g? So what I'm- just doing that at g.
Shanti: Yeah, then there's a problem. [inaudible] at g right? [gesturing, using hands to show directions]
Tom: Then I'm this at g. What if I, if I have a Z component, that acceleration, that's moving at g, therefore canceling out g and if-

Shanti: g. [gesturing]
[Cynthia looks on, looks away, looks on]
Tom: [gesturing] -and at the same time I have a X component of acceleration that's, is equal to g? Then my magnitude is back to g. And then I'd move along the surface instead of in and out of it. *That's what I was saying*.
Shanti: Yeah, that's a good example.
Tom: So there are movements you could take that would just move you across it and not in and out.

Once they have joined him in this space, Tom steps back, reflecting that he does not know how much of a problem this will end up being because he does not know how likely his special case is. He prophetically explains that this special case may in actual practice be transient.

Tom: Now it may be that this magnitude is helpful in the sense that its only particular cases where it would screw up cause that is a very specific case right, and with acceleration, real acceleration in any direction, you're gonna spike up [punching fist out to show movement] for a while and then back down and level out like when I move when I go from stationary to stationary you know I accelerate and I later decelerate and then I'm back to zero, *so it's not like I'm ever gonna be at one of these unique acceleration vectors that screws up the sphere example for very long, cause it's never like constant acceleration,* you know like I'll just take off into outer space like I'm gonna be moving around with acceleration really flip flopping everywhere.

The team reflects on "Tom's special case," and Addai picks up on the possible "uniqueness" of this case and moves towards a designerly perspective:

Addai: So for a realistic?
Tom: It may not matter.
Addai: For a first order approach?
Tom: Yeah.
Shanti: Yeah, it may not even be…
Tom: It may be helpful if not exact.
Shanti: Yeah, but yeah, that's something to keep in mind as a technical challenge. I mean, and so, that if it breaks in those situations which we anticipate that it might, then it might be a step further to take the inclinometer […] and try stuff with that.

They also reflect that they have come to understand something ("Good old high school physics," as Addai earlier describes it), including Cynthia, who has been mostly quiet but attentive:

Cynthia: I seriously just learned more than I did in my entire semester of physics.
Tom: Very difficult. [Shanti laughs]
Addai: It's such a weird notion that you can be moving-
Cynthia: *Yeah.*
Addai: -and have the same vector sum as not moving.
Tom: Right.
Cynthia: That is a weird thing.
Shanti: Yeah.
Tom: That's, that's the whole problem with these accelerometers.

They then jokingly discuss the possibility of creating Tom's special case once they have built the prototype:

Addai: It will be interesting to put this together roughly and actually put the accelerometer on it and see if we can move it-
Tom: Right!
Addai: - that scenario and see-
Tom: Yeah, right. [laughs]
Addai: -see what movements we can do.
Tom: To zero out…
Addai: We could do to get it to zero.
Tom: Right.
Shanti: Huh.
Tom: And if it turns out it's exactly, uh, [laughter] the spasticity test, uh, it cancels every time? [Shanti laughs]

Though this last comment is said in jest, the specter of this possibility stays with the team. During their February 18th interim presentation to their TA, they continue to wrestle with the accelerometer problem. Cynthia brings the drawings and formulas (such as shown in figure 6.4) written during the previous meeting and the TA then recaps the conversation they'd had, restating Tom's special case from the week before in which non-zero motion could appear to be zero. Greg and Cynthia suggest talking to the sponsor will be helpful for understanding this, because they want to know more about the type of motion they will be recording. The sponsor has little understanding of the physics involved, but could provide a demonstration of how the device would move through space. The TA agrees that though this is "not very elegant," it might give the team "some new ideas."

One week later (Feb. 25th), the team is exploring possible solutions. They discuss their ideas with Shanti. The discussion highlights that they have established a shared problem space. Tom has begun designing code in a program commonly used by engineers and has fabricated data to provide an example of what they expect to get. The code he has written allows them to get the information they desire from the data they have fabricated, but they still do not know if this is what their actual data will be like. This exchange shows how Addai, Shanti, and Tom now fairly equally participate in the discussion, as compared to previous discussions, and demonstrates a shift towards more designerly and practical action. Cynthia and Greg still attend but do not contribute much to conversation, though both can be observed participating in subtasks and through their actions, demonstrating an understanding of the problems the team is dealing with.

Addai: I guess this probably should have been in-for a question a few weeks ago but it seems like a lot of this problem comes from the fact that in the baseline acceleration you have, uh, different sources of error coming into it and then as you integrate those sources of error you may propagate, become more and more prominent?

Tom: Yeah.[…] -and that's why I'm sort of, if you have the noise and, and other sources of error that are centered about zero as you integrate those effects will become less and less. […]

Addai: High frequency stuff you don't have options. Is it possible that we could do this on top of just the acceleration data itself? And not worry about velocity and so instead of looking at these big changes in velocity we can look at, like, instances of acceleration? You know? I guess if you were taking it through constant velocity about a zero acceleration?

Tom: Ummhmm.

Addai: And then we could become interested in when the acceleration changes from zero probably to, like, a negative value and how quickly that change occurs?
Tom: That might be possible. Uh, yeah we'd have to- it's tricky to say, as far as you know, one just moves in positive directions versus moving in a negative direction because the orientation problem.
Addai: Right, right.
Tom: But as a problem as well, but if, we if we can rotate the data around so it's in some proper-
Addai: yeah and so
Tom: -alignment.

During this exchange, they have begun considering that Tom's special case may not be a problem if they just want to get an approximation of the motion, demonstrating a gradual transition from theoretical to design problems. As they continue to discuss this, Addai is uncertain, but Tom is receptive and affirms his idea:

Addai: So really we could just look for a change between the way the data has been going and then some sort of cause that data to shift in the other direction.
Tom: Mmhmm.
Greg: Discarding attempt to get velocity profile.
Addai: I'm just throwing it out there.
Tom: Yeah, yeah, yeah.
Addai: But I don't know if it's right or wrong, but it seems like it might be easier to go about it that way than just running everything through a low pass filter.
Tom: Yeah, and so these are all things that we can certainly try in software, uh, later. I mean that would be very reasonable.

The team has now spent a considerable amount of time speculating about the possible impact of the accelerometer problem and Tom's special case, but now, as a team, have some ideas about how they might address it. They continue to shift towards a design perspective, which Tom expresses hesitantly and awkwardly in this instance and which Shanti encourages:

Tom: So I think, I'm actually, you know, this is, this is, you know, stuff I'm thinking about, it's probably less important right now than our primary goal is, is getting the hardware done, uh, and getting something we can sample.
Shanti: Yeah, one other thing I was wondering was like, um, it's good to speculate ahead of time what sort of noise sources you will expect-
Tom: Mmhmm.
Shanti: -but maybe things are gonna change when you actually capture the signal, do you know what I mean? So things might be less ideal or more ideal that what you're anticipating.

Later, in the EE lab, Shanti and Addai talk over another device they plan to incorporate into their prototype, a pressure sensor. The lab is noisy and there are lots of students coming and going, working around computers and other apparatuses. The team has a computer to which they connect various devices (Figures 6.4 and 6.5), creating a shared working space and this leads to less conversation, more pointing (Figure 6.6). They discuss lines on the screen produced from the pressure sensor. There are two lines and they try to decide if one is filtered, saying that it looks like a filtered version because it is "smoother" and "time delayed," but they have not placed a filter in the system. Shanti points out that averaging is a type of filtering. They use trial and error, messing about with the system, adding a filter, changing its parameters (.5, 30, 100) to see what happens. Sometimes one thing is varied at a time, but not always. No decision is reached about what is happening. Addai tells me "This is engineering."

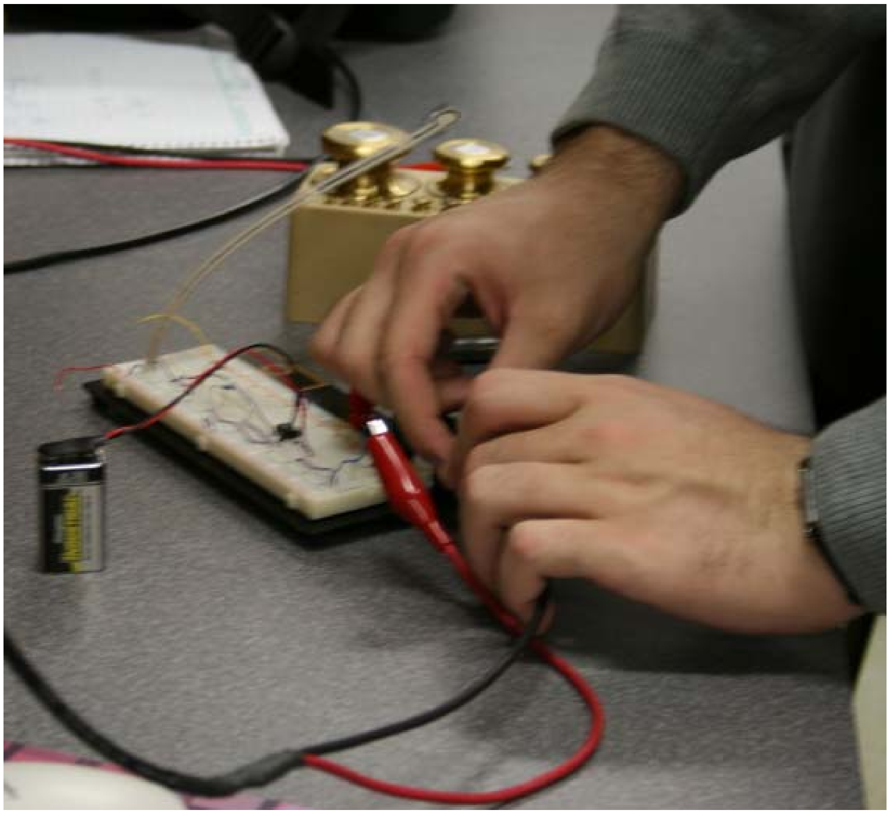

Figure 6.4. Addai connects their device to the computer

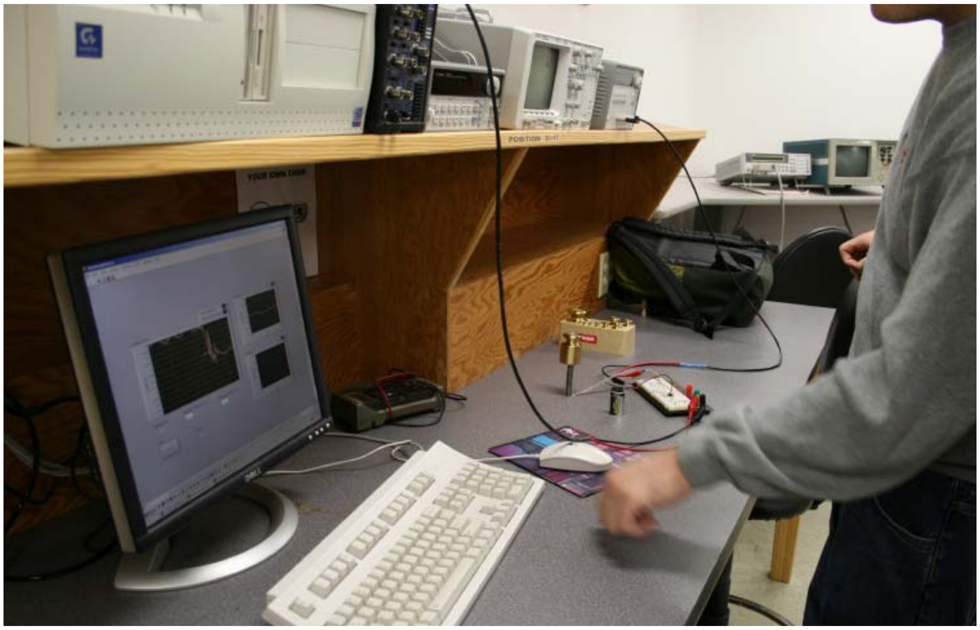

Figure 6.5. Addai confirms that they are getting information from the devices (note graph on computer screen).

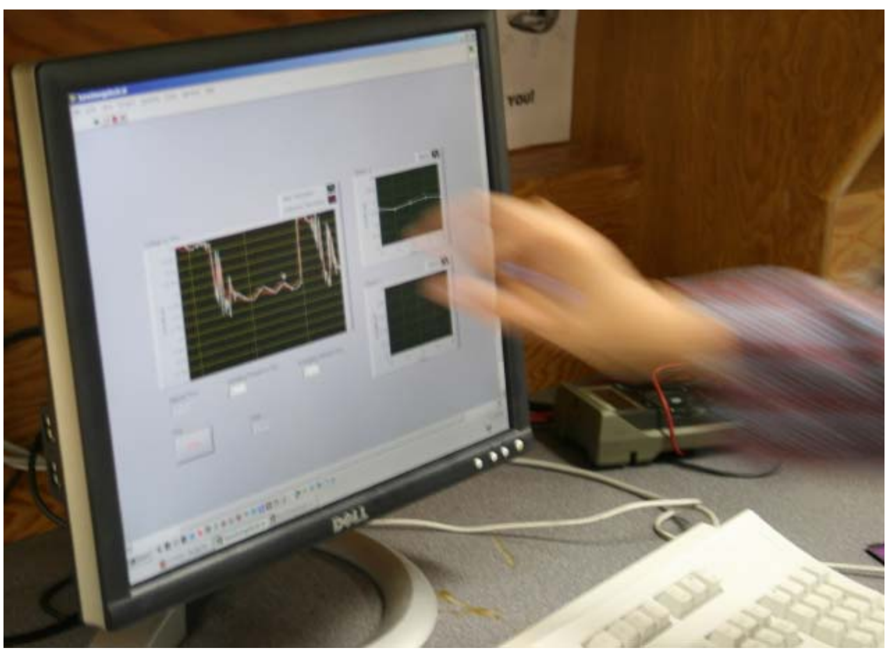

Figure 6.6 Shanti points to the graph on the screen, asking for clarification about the meaning of the peaks

The second sociogram (Figure 6.7), constructed from the social network analysis data and observations of the team from this time in the team narrative, is very similar to the previous representation. The sponsor is now located further from the team, as during this time they have been perseverating on the impasse in a largely theoretical space, somewhat more removed from the design goals. Cynthia, who continues to seem slightly removed from the team, is once again located somewhat removed from the now equidistant Tom, Addai, and Greg. The TA is shifted towards Addai, as she often encourages or supports Addai's ideas. The Faculty Advisor continues to hold a relatively unimportant role. As with the previous sociogram, the ratings are very Cohesive.

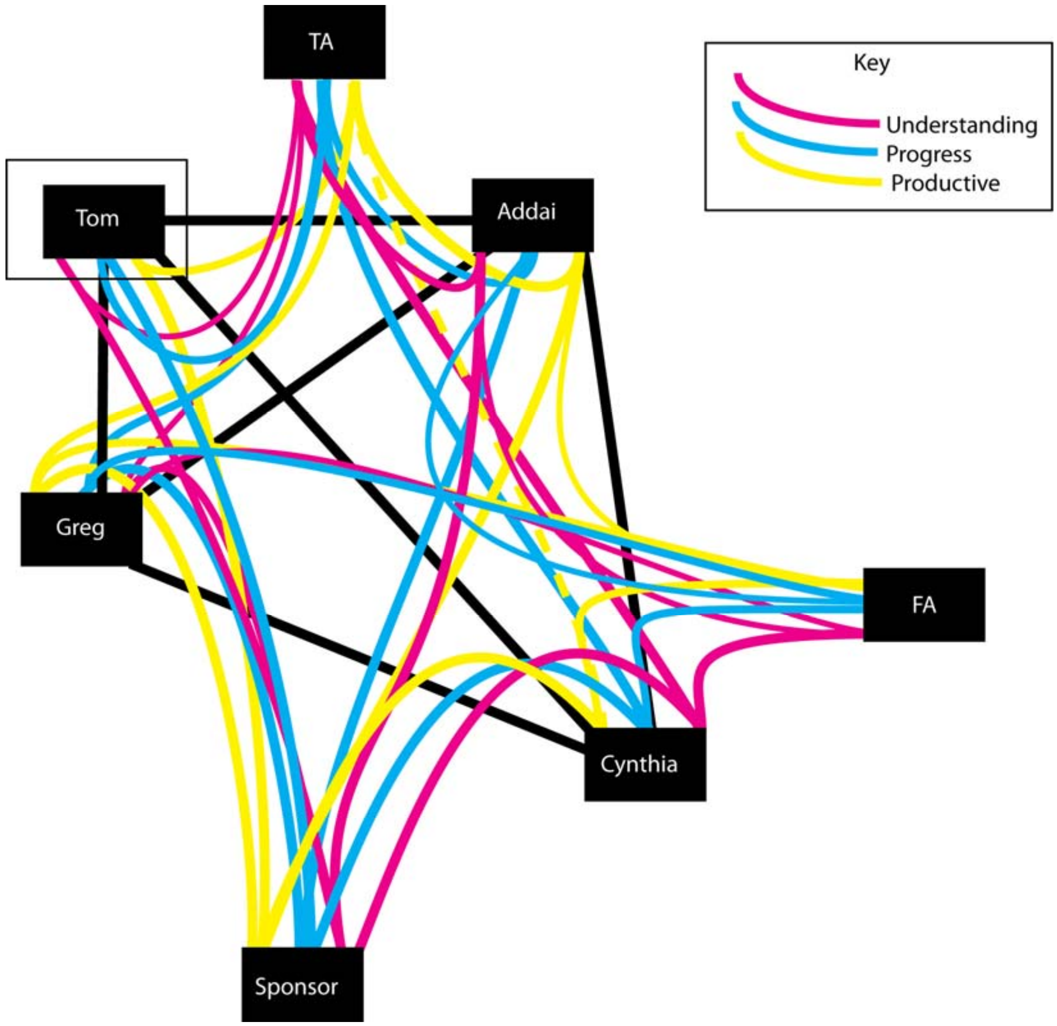

Figure 6.7. Hybrid sociogram of team interactions

At the March 31st weekly TA meeting, Addai explains to Shanti that their possible solution to the accelerometer problem is not correct, though they do not yet have experimental data. They do not explain why it is not a workable solution, and Shanti does not probe further, in part because they spend much of the time discussing the more proximally solvable problem of calibrating their other device, the pressure sensor. Because they now have accelerometer data with which to experiment, they speak in more practical terms, of voltages rather than vectors. Note that these are not yet data that reflect the actual motions; rather, these data were collected for calibration.

Addai: We need to translate the accelerometer data into some sort of a meaningful quantity, right now it's just voltage.
Shanti: umhmm
Addai: It's not that voltage isn't necessarily meaningful but it's tough to justify how to deal with three different axes of voltage data.
Shanti: Right.
Addai: Isn't really appropriate to convert that to one aggregate. I think those are the big challenges right now.

Approximately one month later (April 21st) the team has collected some experimental data and has begun to construct a solution. They explain their findings to Shanti during a weekly TA meeting, but as the solution does not address Tom's special case, she is skeptical about their solution. Greg has contributed much to the testing and solution, but is not in attendance at this meeting, and Addai is unsure of how the solution has been addressed. Note that this solution is a re-visitation of Addai's original suggestion to sum the vectors:

Addai: Calibrated the accelerometer and by doing a square root of sum of squares-
Shanti: Mmhmm
Addai: -[Greg] says that it works the way it should.
Shanti: Okay.
Addai: And we subtract out gravity. We just [inaudible] orientation.
Shanti: So you're taking the sum of squares? Uh, and then you're subtracting out gravity how?
Addai: We're adding the square root of the sum of squares. First, what we do is we convert each of those by the calibration curves to the unit per second squared-
Shanti: Okay.
Addai: -and then we have three axes [inaudible] sum of squares square rooted-
Shanti: Okay.
Addai: -and then we just subtract gravity 9.8 meters per second per second.
Tom: It's basically getting a, uh, net acceleration magnitude.
Shanti: [looks concerned] Right?

Tom: And, uh, which is one contribution of gravity and then mechanical contribution from movement.
Shanti: And we don't anticipate any situations like we talked about where the two components would cancel out?
Tom: Oh, yeah, like moving around? Only transiently.
Addai: We don't anticipate it, we're gonna look at it.

For Tom, this designerly solution has become a possibility by considering the additional information provided, not by including an inclinometer (which has turned out to operate much as the accelerometer and would therefore not contribute additional information), but rather by considering the information from the pressure sensor:

Tom: So I think it will be really interesting when we get, when get, accelerometer working as we expect to, to look at the two, at velocity and speed anyway, speed and pressure at the same time, figure the graphs will be related.
Shanti: Most definitely.

Shanti asks them to relate what they are measuring to the biomedical need, to clarify how their measurements correspond to physiology. This keeps the focus designerly and on the needs in the situation. Cynthia takes this up:

Shanti: So what is like a physiological, um, aspect? What physiological aspect are you measuring when they try to see the whole range of motion where a spastic event occurs, what does it tell them? I'm just curious.
Cynthia: Physiologically?
Tom: Um, we're not sure, or I'm not sure, that is definitely something that is, uh that is something she said.
Cynthia: I'll email [the sponsor] on that one.
Addai: We're gonna visit with her tomorrow.
Cynthia: Yeah, that's a good question.
Tom: So for us, as to why were looking at that, Voice of the Customer.
Shanti: Right yeah, I'm just curious.
Addai: I think, then we'll ask her, just to make sure but I think what it is, you adjust the pressure measurement-
Shanti: I see.

Addai: -‘Cause you'll have, again, I think, you'll have, if you have a lot of electrical activity, a lot of hyperactivity, then the spastic event will probably take place at the very beginning, it won't take a whole lot, uh, if you have slightly less than that. The spastic event might take place at [inaudible] after you…
Cynthia: Yeah, but what if it's like extremely rigid at the end? What if it's like…
Addai: That's why I think that the first thing to do, and this is what I put in the, uh, proposal, the first thing you do is look at that pressure value and have that make your sort of first order approximation.
Tom: Yeah.

Next, Addai and Cynthia demonstrate that they can detect differences with the pressure sensor by simulating three tests with themselves (Figure 6.8). The results are clear, showing as Tom says “a tenfold increase,” and Shanti says this progress is “pretty cool!”

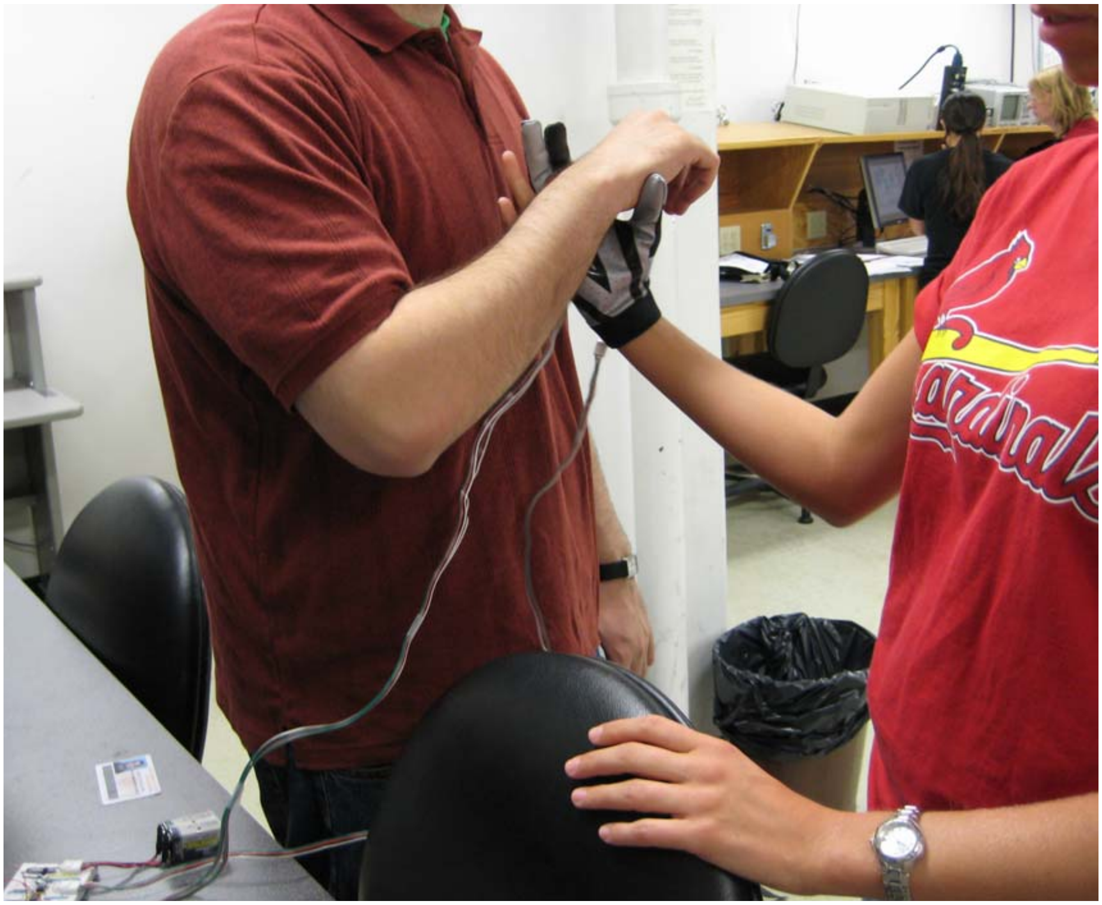

Figure 6.8. Addai and Cynthia demonstrate the device

When Addai asks if she has any suggestions for their accelerometer problem, because he has picked up on her concern over their proposed solution, she admits that she does not understand their solution:

Shanti: Well, I don't understand exactly the whole, uh, minus g thing quite honestly. I see that you're, I see that you're combining them with this mean square term because, let me think about this a little more, um…
Addai: When you say you don't understand?
Shanti: I don't know how you could just sub- I'm not seeing how you could just subtract 9.8 and that would do it?

Addai: Well, the idea is, imagine a case where, uh, there is no motion, so the accelerometer is just in a position like it is now, just arbitrary position where gravity is affecting-
Shanti: Right
Addai: -all three axes but affecting them at different angles
Shanti: Right.
Addai: So if you were to do the combined thing where you take the square root of the sum of squares-
Shanti: And 9.8?
Addai: -you should get 9.8.
Shanti: Right I agree, and so…
Addai: That should hold true no matter what the orientation is and no matter what the external or other acceleration is.

Shanti still does not see how this addresses Tom's special case, and together, they explore several possible cases. The first case they chose works fine, but the second results in an unexpected outcome, and this leads them to consider Tom's special case again:

Tom: There may be some special cases.
Addai: I'm convinced that it's not Tom's special case. We're good.
Shanti: Yeah, the special case?
Tom: The special case where you're like, if you're accelerating at 9.8 orthogonal.
Shanti: Then you're getting 9.8 plus 9.8 ...squared.
Tom: They wouldn't just add because you're doing the sum of squares thing.
Shanti: So you would have square root of 9.8, right? Squared root two times 9.8.
Tom: Yeah.
Shanti: Right?
Tom: So it'd be sort of funny when you're moving orthogonally to gravity. […] So there is some m that will give us zero. So that would be erroneous.
Addai: Well, is there really a movement that will give us zero?
Tom: There would have to be.

Thus the theoretical exemplar continues to haunt the team. Though they have begun to converge on a practical solution, it is troubling to them that it does not address Tom's special case. Though at other times Tom has described it as "transient" and therefore not a practical issue, at this point they focus only on how their current design solution cannot account for Tom's special case.

The sociogram, constructed, as before, from social network analysis data and observations of team interactions, is similar to their previous sociograms (Figure 6.9). The sponsor is still distal from the team and closest to Cynthia, but is somewhat closer than previously. The team member locations demonstrate how subtasks have been managed during this phase of work: Tom and Greg have been working together on the accelerometer while Addai and Cynthia have been concurrently working on the pressure sensor. Cynthia has been moved closer to the team because her contributions have become more salient and apparent as they have begun to move beyond the impasse and adopted more of a design perspective. The TA is located closer to Addai, again to show her support and encouragement of his ideas. The faculty advisor is even further from the rest of the team now, and has played a very minor role in the project. Note that Addai did not complete the survey at this time point, and his relationships are based on observations, and are therefore represented with dashed rather than solid lines. The team did not seek out additional mentors in any significant way.

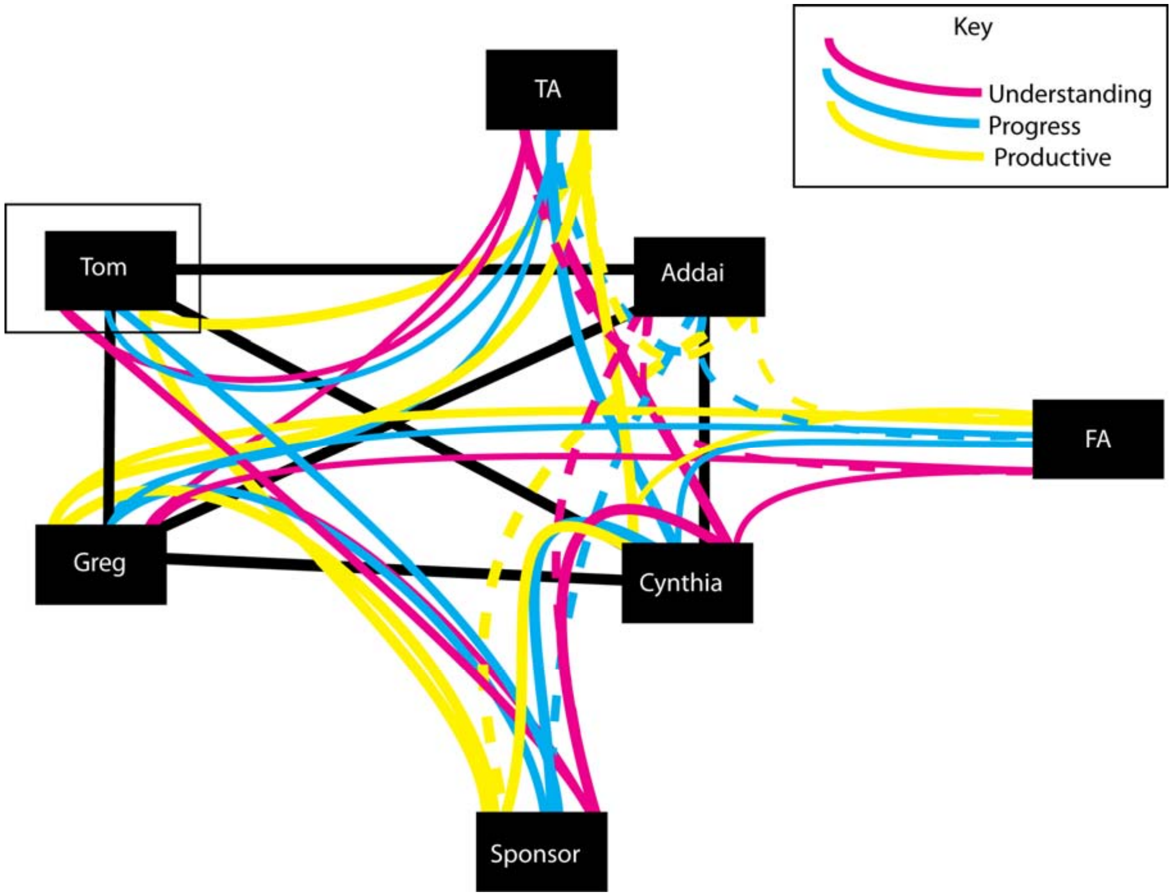

Figure 6.9 Hybrid sociogram of team interactions towards the end of the team life history

At their May 1st final presentation of their design, the team has refined their solution to the accelerometer problem through practical experiments which have demonstrated that Tom's special case, which had so beleaguered their thinking, was at worst transient and in practice, nearly impossible to provoke. The course instructor, Dr. Davies, and another faculty member, Dr. John, along with the sponsor are all in attendance.

Greg explains how they chose the devices they incorporated into their prototype and explains how each works. He then introduces their solution before explaining why the accelerometer was a problem, then revisits their solution.

Greg: We initially assumed that it would be advantageous to measure all three axes of spatial acceleration, uh, after doing some testing though we came to the conclusion that only one axis is capable of giving meaningful information. So after doing some clinical simulations, we, uh, I'll explain a little first. Uh, so if the accelerometer is balancing in the back of the palm and we call the axis going through the Z axis and any sort of typical, uh, spasticity assessment motion in the direction of the applied force will always be in the direction of the Z axis and so indeed as we have looked at, uh, data we have acquired the Z axis data contains recognizable features that we can correlate to events that occurred during the tests whereas the X and Y axes really give little or no additional meaningful information so we decided just to use the one axis from here on out.

Then Tom explains their process and solution further:

Tom: We went about testing the device to see if you could really measure the sort of physiological data we set out to measure. […] We expect our acceleration data to look a little like this. If you look at the real data we acquired however, […] it doesn't exactly look like that so, so, what was wrong? […] It has some features we expected to see […] but you can see this offset change, um, between beginning and end of the test so the problem we were experiencing was the accelerometer was sensitive to both motion related acceleration and the effects of gravity. […] The killer is what's giving us this offset, so how do we separate these gravity contributions from motion contributions? […] Our reasoning here is that […] the gravity contributions represent the low frequency content of our acceleration data- the motion related acceleration conversely will be mostly represented in the high frequency content because, um, the, uh, the motions that we're doing are pretty quick- you have both positive and negative acceleration- will be very transient because we're not really taking off to fast speed and returning to, uh, returning to a standstill. So what we decided to do is low pass filter the acceleration data. […] We then simply subtract the gravity contribution to get this corrected motion and as you can see, um, this actually looks a lot like the data we predicted.

Tom goes on to describe their clinical simulation testing, which was also successful, and clearly shows a relationship between the two sensors. At the end of the talk, the sponsor and other attendees pose questions for the team.

Sponsor: The adjustment that you made for gravity, um, very interesting- boy! I didn't even realize that that was going to be a contributor but now I'm wondering about the measurements that are actually done in the horizontal plane because there are a few that will show up in the horizontal plane. How, how will, will the device accommodate for the absence of gravitational input on those measurements?

Tom gives a somewhat complex response to this (naïve) question (gravity is always affecting it), and then Addai steps in to simplify the response:

Tom: Sure. Well the algorithm that we used is subtracting out the, the constant contribution of gravity no matter what that is so if we were in the example of the hand being directly in line with gravity it's measuring a hundred percent of the gravity, um, and the test is actually pushing down, then stopping. It would have the same amount of gravity contribution at all times in our algorithm. We'd completely remove it and everything would be fine in your example. Supine- we're moving completely across the table, uh. Two things first is that when the hand is in this position the gravity contribution should not affect the Z channel so it affects it most if your hand is directly down and if it doesn't show up in the data at all if your hand is sideways, um, but more importantly, no matter what the orientation is, as long as your hand doesn't change very much or changes very slowly it's orientation with respect to gravity, this algorithm will remove it the same so it should work the same if you're moving sideways or if you're moving down.

Addai: The short version is that little red curve that's derived just depends on how gravity is affecting the sensor. If it’s not affecting the sensor at all the red curve should be-

Tom: Yeah, zero. It’d be subtracting practically nothing. It would be as it is.

Sponsor: Cool.

The course instructor then asks the sponsor whether the team has met the design requirements:

Sponsor: The only hope I had because I'm naïve, was that we could take it even further in this semester but absolutely I think- so you know we've unearthed a lot of nuances that I, -I'm not an engineer- I didn't anticipate. But I really see even more clearly that it’s a viable possibility to create this thing and before, it was, before I had a dream list of three things or four things that I would like to see become three dimensional and I think this is phenomenal. Because it really is -they're bringing a lot more data to this than has ever even been questioned. So yes! So, I think it's very applicable.

Dr. Davies then goes on to question the team about their solution:

Dr. Davies.: I do not understand, uh, how y'all came to the conclusion that you described that movement in a single Cartesian coordinate Z axis.
Greg: Well the coordinates are in relation to accelerometer itself so you're, uh, so if the clinician is grasping the limb-
Dr. Davies: Uhhuh.
Greg: -uh, thusly, [demonstrates the motion] then this is a typical range of motion is like this and then rotational.
Dr. Davies: Okay so I'll understand that so you have a moving frame of reference for your accelerometer. […] So if you were to plot velocity of the accelerometer, still seems to me- [gestures to demonstrate] if I've got an X Y Z right here. Let's see X Y and Z. So X is along the edge of the table and if I can twist myself around this way I have movement through Y and Z correct?
Tom: So I think one way to look at it is that the, the moving frame of reference for the hand.
Dr. Davies: Mmhmm
Tom: It would present a problem if we if our accelerations were always being measured with respect to the ground.
Dr. Davies: Mmhmm.
Tom: So if our sensor is- when it's rotated around- keeps its orientation as it rotates through X and Y that would present a problem, but the accelerometer itself is rotating while the limb is rotating so there is a moving frame of reference, but it's moving correctly. The physicians hand is moving and the limb is moving so you're always get the component of velocity that's in the direction of applied force which is what we were looking for. […]
Dr. John.: Since this is a planar study why didn't you create a device that is planar that you say on a table top? It would keep it distinctly in a plane and gravity would not be an issue if you're on a horizontal table top.
Cynthia: It's often difficult to position the patient. […]
Dr. John.: You need to go where the patient wants to go.

The team has been able to successfully create a prototype and can now justify their practical solution to the design problem. They struggled to define their project as a design project, and had this occurred earlier, they may have been able to iterate upon their solution and incorporate more innovative ideas that arose when they talked with their sponsor about next steps.

On their early design work, they were rated by experts as having four out of five on Efficiency and a three out of five on Innovation; For their final designs, they were rated as a five on Efficiency and a four on Innovation.

The team's Cohesion actually decreases over the course of the semester, opposite the trend of the class as a whole (Figure 6.10) (Note that higher levels of Cohesion are represented by lower numbers).

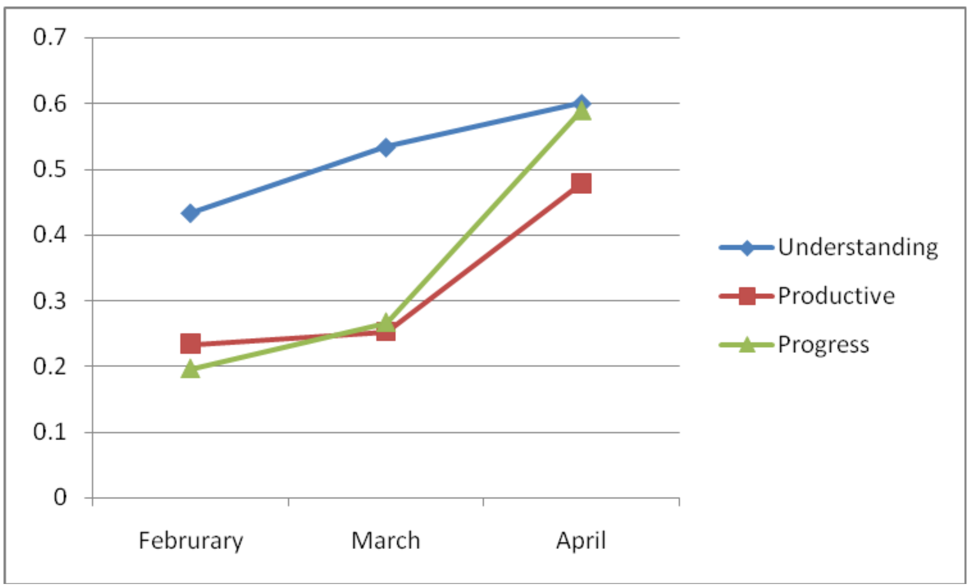

Figure 6.10. Team Cohesion over the spring semester

Team 3.3

Team 3.3 is a four-member team with three native English speakers: Menaka, a South Asian American woman, Shawn and Colin, both Caucasian men, and Todd, a native Mandarin speaking Chinese American man who prefers to use his "American name" to his given name, which is Chinese and "hard to pronounce." Their teaching assistant, Sanjay, is a young South Asian American man, in his second year as a TA for this class.

Their sponsor and faculty advisor are the same individual: a biomedical engineering professor who has sponsored a project in the past, but who takes a less and less active role through the year. This role is taken on by a staff member who has a background in engineering and who runs the labs and equipment. This is no less appropriate as their sponsor/faculty advisor had little expertise about their project. They also get guidance from various people at NI, the manufacturer of their device. Their project is to design an interface for an Instron (Figure 6.11), a device that measures tensile and compressive forces in materials, such that it can interface with LabVIEW, software commonly used in engineering.

Figure 6.11. The device the team is designing for

The time line of the design team's life history (Figure 6.12) follows similar timing to team 3.2 in terms of when their impasse emerges. Also similar to team 3.2, the impasse that team 3.3 struggles with is recurrent and various possible solutions are rejected during their design process. In contrast to team 3.2, this team settles on a final design solution path earlier and consequently has more time to iterate on that solution.

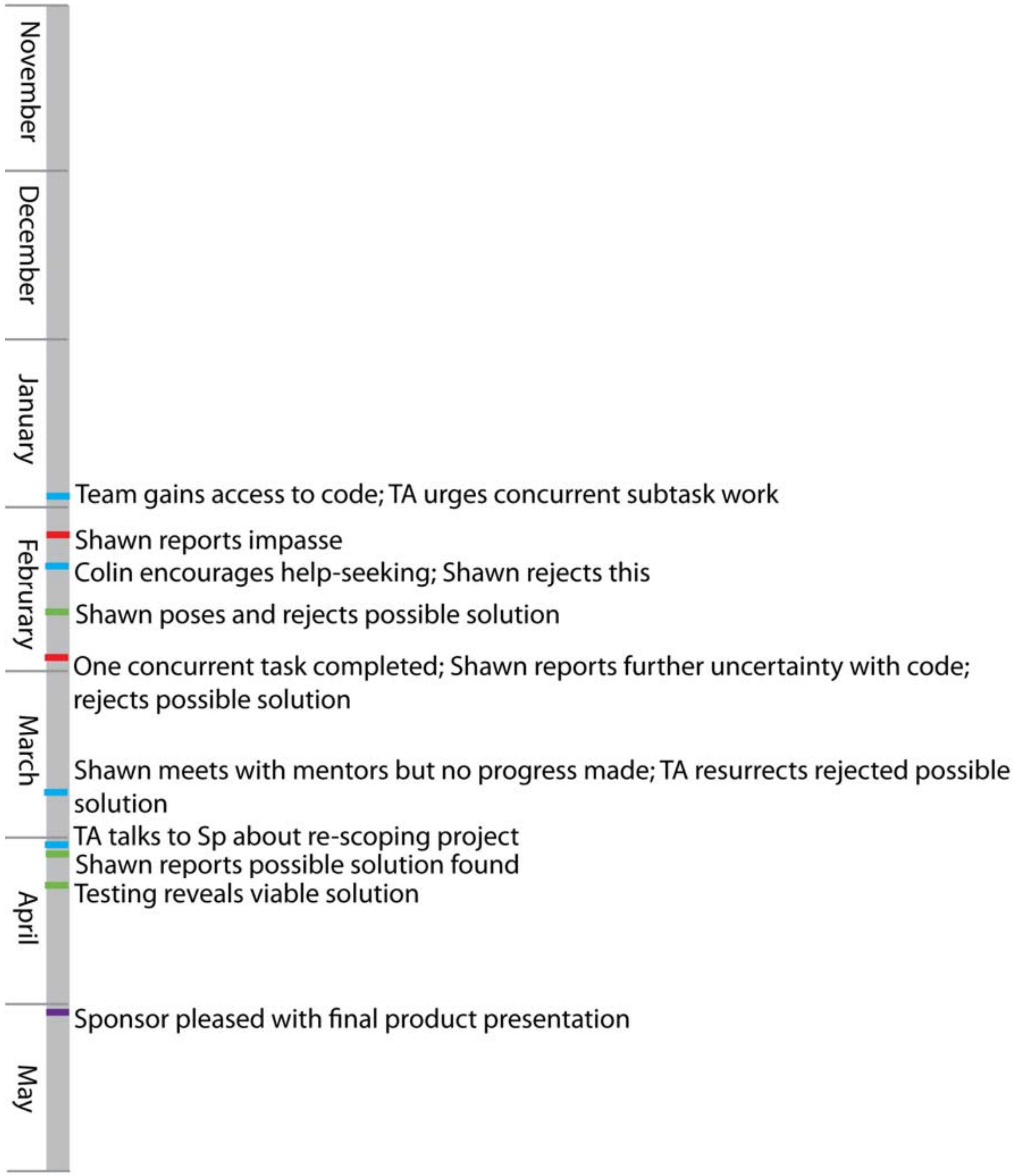

Figure 6.12. Timeline of the team's impasse

This team faced challenges during their redesign project, which was not as successful as they had hoped, and the professor explained they did not "heed the VOC." This is attributed by the TA and the professor to one member's personal knowledge of the device.

It is worth noting that although the team seems to be in a situation similar to that of the redesign project, in terms of having personal familiarity with the device being redesigned, this will prove to be less problematic for the sponsored project. This may be attributed to the fact that in this instance, their own list of needs matches those given by other customers and the sponsor, whereas for the redesign project, the need they addressed was not a principle need from other customers. Next I highlight themes then present the team narrative.

Origins of an Impasse: Theoretical versus Practical Perspectives

Team 3.3 begins with more of an engineering perspective than other teams, perhaps because they have a device in hand to modify. However, they yet face an impasse that predicates on the emphasis of scientific perspectives: Their past experiences have provided them few cases to use as exemplars for overcoming the impasse they face. The team is initially confident about their solution but cannot predict where they will struggle until they begin working with actual materials, at which point they realize it is much harder than expected. Initially, only one team member has much experience with electrical and computer engineering, a key component of their project, but his experience is more theoretical than practical, and he struggles to appropriately troubleshoot. That only one member has this experience leads into themes related to how the impasse is negotiated.

Strategies for Negotiating an Impasse: Locating Expertise

To resolve the impasse faced by this team, the emergent team leader seeks help from outside mentors and shields his team mates from the impasse, while giving them other tasks to address. His team mates do not generally negotiate these tasks, and do not always seem to understand how the tasks might interrelate. In an expert system, this division of labor might be quite effective and it did result in a product that experts perceive as innovative, however, at the end of the project, only the emergent team leader understands why the impasse occurred and how it was resolved; this is because the team effectively included a secondary hidden design team populated by other mentors. The team leader is unwilling to teach his team mates about the problem and is not receptive to their suggestions.

Team 3.3 and the Hidden Design Team

The device the team is redesigning for, called an Instron, is used to test the mechanical strength of materials, and many of these students have used it and are familiar with the problems that occur when using the device. These problems are not related to the device itself, but rather to the handheld computer that is needed to run it. They have interviewed an engineer who supervises some of the labs and who keeps the labs in good working order. During the January 24th weekly meeting with their TA, the team explains their plans for the project. They are guided by both their Voice of the Customer interview and their own experience with the Instrons, which have the following problems according to Shawn: "Speed is an issue. […] Testing nine samples might take an hour, it should take 20 minutes" and Colin explains that they "break a lot!" and offers that the lab manager has to therefore "fix them frequently."

They gain access to the program code in late January and initially predict that going through the code will take "a couple of days." The TA urges them to work "concurrently" because dealing with the code will be time consuming yet should not hold up other aspects of the project. They then mention two other tasks that may be worked on concurrently: creating a cable to connect the Instron to a desktop computer and working with the LabVIEW software.

The sociogram constructed from social network analysis data and observations of team interactions (Figure 6.13) shows the lack of Cohesion in this team, visible by examining the relative thickness of the connecting lines.

The faculty advisor and sponsor roles are played by the same person in this case, but there is a secondary mentor the team interacts with frequently. This secondary mentor holds less importance initially. The sponsors are located at the bottom of the graph because although they give the team a fairly constrained task, they do not monitor progress or direct the team towards a solution. They act more as customers than as sponsors. In fact, the team interviews both of them for their voice of the customer activity.

Todd and Menaka are both more distal to the team and they are observed to interact less and contribute less to the team. The dashed lines indicate that Shawn did not fill out this survey, but relationships were observed and inferred.

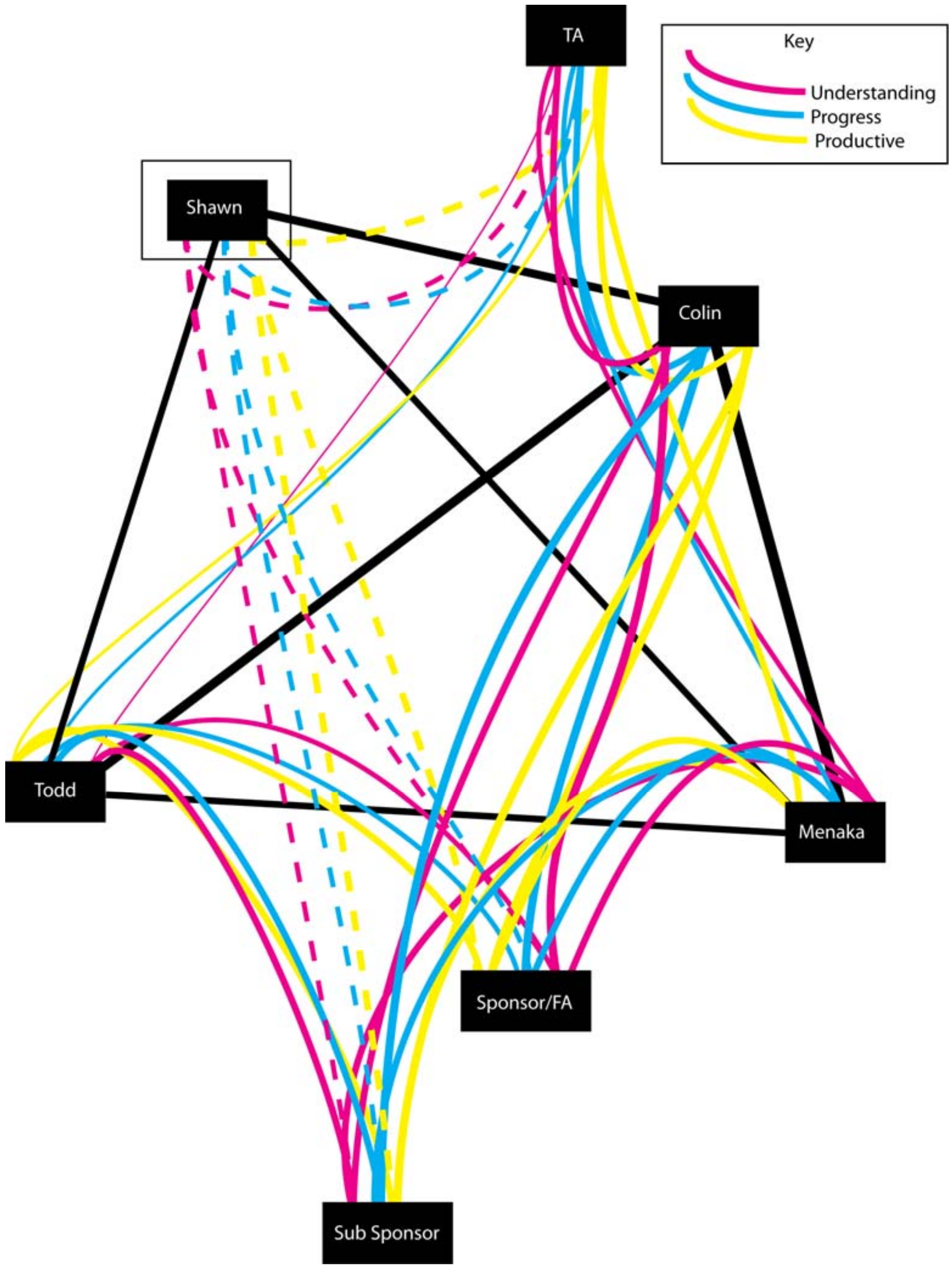

Figure 6.13. Sociogram of team 3.2 from early February

Two weeks later, (Feb. 7th) Shawn has begun looking at the code, and has discovered that a critical part of what they need (to understand how the Instron sends and receives information) is not in the code they have been given. This part of the code is proprietary, and though the Instron manufacturer is helpful, they are not able to get access to the entire code and they have to either "figure it out or emulate" it, as Shawn explains. Emulating it would solve one of the problems- that the hand held computers frequently break- but would not address the speed issue.

On a survey completed at this point, one student complains: "One of my teammates is very hard to work with. He obviously haven't read the team handbook and strikes down ideas of other members so that he can get his ideas through," but another explains "We all seem to get along very well. Our sponsor has given us pretty much as much support as she can and my teammates that aren't doing as much simply lack the previous experience to be more helpful."

At an interim presentation one week later, they discuss progress made on one of the "concurrent" tasks (the cable to connect the device and a desktop computer, Figure 6.14) but have not worked on the LabVIEW software and have made little progress on how to move forward with the code. Their TA, Sanjay, encourages them to work concurrently ("Maybe we talked about this last time, but is it possible to concurrently make a LabVIEW module?"). As for making progress with the code, Colin suggests they meet with NI, the company that manufactures the Instron, the next day, but Shawn explains that it would be "pointless" because they have not made progress since the previous meeting. He explains further: "I still have to go through the C code and figure out, uh, the order of the command strings and stuff like- 'cause we haven't translated anything yet, still have to do that. So, I was hoping someone else would make LabVIEW thing." Shawn goes on to describe what it should look like, glancing at Colin as he does so, and explains the other tasks that need to be accomplished. Among these tasks are acquiring some circuitry supplies. Sanjay suggests some people he could contact for these supplies and Shawn asks for clarification on finding these people, explaining that he doesn't "know many people."

This interaction shows a recurrent trend in which Shawn explains to the TA what the problem is, Colin attempts entre into that space, and Shawn steers him away by either rejecting his input or by suggesting that “someone” should work on the LabVIEW software. Since Todd and Menaka have been delegated and are completing other tasks (for instance, the cable and preparing presentations) the “someone” seems to indicate Colin. Shawn is not receptive to his team mates’ suggestions.

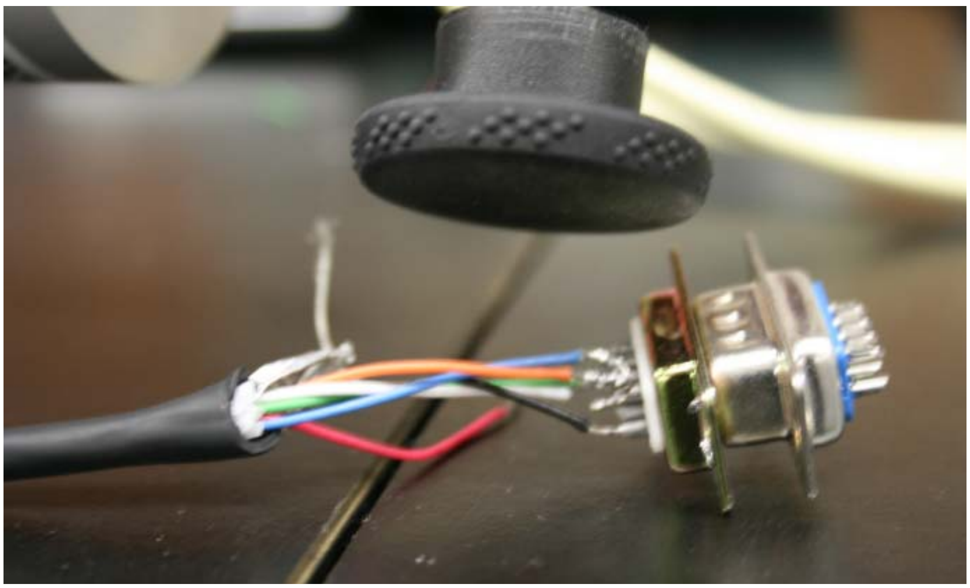

Figure 6.14. One of the concurrent projects: creating a cable to connect the devices

One week later, (Feb. 28th) they have completed the cable and Shawn has attempted to use the desktop computer to run the Instron. He explains that he does not know why it did not work, and Colin reassures Sanjay that they will get help:

Shawn: I don't know if that's because the wire was broken when I tried or […]- like I said I'm not sure if that's because the wire was broken when I tried, so I only noticed the wire was broken when I left - I was like, Oh! It's broke! No wonder I couldn't get anything to work. […]

Sanjay: It hasn't worked. So why do we think that is?

Shawn: I don't know how it's used- serial stuff with LabVIEW very well- so it could have been anything. Um, I sent, I sent an email yesterday once we had cables and voltages and stuff to R and I people and-[…]
Sanjay: So you just haven't figured out how to use LabVIEW to send?
Shawn: Right.
Colin: I think NI is going to help us with that part, right?
Shawn: Right.
Sanjay: Good.

Shawn is frustrated with their progress and unsure of how to proceed, but considers that the software may be of use. Colin makes a suggestion, but Shawn sees it as a misunderstanding of the problem:

Shawn: The only other thing that I was hoping to have done by now but we don't is, uh, we can see the voltages, like, what's high and low, like the max range, but, uh, we haven't been able to translate that into bytes and stuff yet. […]
Sanjay: And how do you plan on doing that?
Shawn: Things in LabVIEW that we can use but-
Colin: There is an oscilloscope VI [Virtual Instrument]. I kinda had it set up, I have to figure out how to set it up.
Shawn: Oh, no! So, there are two different things. So, there is the oscilloscope that you have and then you can use the [inaudible] module in LabVIEW.

As they discuss next steps, they focus on how to use their resources at NI. Colin is emphatic that they try to contact NI again but Shawn is hesitant because they have already sent an email, and he is willing to keep trying on his own:

Shawn: So at this point we have what NI said we should have before talking to them again so-
Colin: Have they responded yet?
Shawn: No. I got an automatic email back from one of the guys saying he's out of town […] so he won't see it til tomorrow.
Colin: That's okay.
Shawn: Yeah, um.
Colin: We can definitely try to make, when we can early as we can tomorrow, let him know. […]

Shawn: That was kind of my plan for the weekend, like, and tomorrow if we can't do with NI, try and keep going forward without them.

As Shawn considers what help they could most use from NI, Colin makes a suggestion that Shawn sees as irrelevant. His unwillingness to entertain suggestions stands in contrast to Team 3.2's team leader Tom:

Shawn: I wanted to talk to NI about how best to use the code to help us simplify our communication.
Colin: That and NI would know how to get us started on, like, okay, this is a blank VI that has everything in place for serial communication and you just have to feed it different commands- be good if they can get us started.
Shawn: Well, I mean, that's online. I started with that.

Finally, Shawn brings up a possible solution, which in his Feb 22nd design journal entry, he describes as follows: "Bad Idea!" though he does not describe it as such when presenting it to the team. Sanjay and Colin take the idea up, but Shawn discourages them by saying he doesn't yet know if it would work:

Shawn: So, and that- that's what I wanted to ask NI about, is we could do it to where we basically made a table of hex commands and related them to English, um, but there are a lot of commands and that would take a while, a lot of time. We could do it, um, but, or we could pack- change the code enough so that it would work on a windows based machine and that-
Sanjay: Yeah, yeah, now I understand. I mean that approach is time consuming but it's easy […] it's just, very cumbersome. […] How many commands are there?
Shawn: Lots...[laughter] And- and- a lot!
Colin: Well, we could ask NI what would be better because, I mean, if we had to, there's four of us, we could just take chunks of the commands, all do it together the first time so we know how to do it and then- […]
Shawn: Um, I think, right now I'm not sure, like, how exactly to do it. I don't want to make us all go do it and then half the table's wrong cause made a mistake or something.

It is unclear why Shawn presented this idea if he was reluctant to consider it. Once the idea has been presented, it remains as a possibility. Colin in particular considers it feasible and would prefer to have an expert from NI direct their activity. Shawn places less confidence in their mentors at NI, and recognizes that their mentors may not know or may be too busy to provide the help they need. The team again discusses contacting NI for assistance, and Shawn first protests that their mentor is out of town, but then offers a further concern:

Sanjay: Obviously any help from NI using serial would be great as of now.
Colin: Now is when we really need them.
Sanjay: So are you emailing that contact you've been emailing, Shiv or whatever?
Shawn: Shiv, and uh, the guy we met with when we went that one Friday - he gave me a business card so I've been emailing the two of them.
Sanjay: Okay. Okay. Alright well, keep going at it.
Colin: I think we should actually, we emailed them back, maybe we should call Shiv.
Shawn: I mean, he won't get back today.
Colin: Well, it doesn't matter.
Shawn: He'll be back tomorrow. I mean Shiv got the email too.
Colin: And he hasn't responded.
Shawn: Well, he travels a lot. He's not usually there so I kinda felt like he was handing us off to another team when we went.

Towards the end of the meeting, after Sanjay has left, Colin asks me how they are doing in comparison to other teams. I tell them they seem fine, but Colin is concerned because they did not do as well as they expected on the redesign project. One of the problems with that project was that there redesign path had been decided prior to collecting customer needs because they had personal knowledge of the device. I encourage them to use their next interim presentation as formative feedback.

At this point, Shawn is frustrated by their lack of progress, but his interactions evince that he has not brought his team mates fully into the problem space. Further support for this comes from a survey completed the first week of March, in which his team mates comment that Shawn has contributed significantly to the project, explaining that Shawn “contributed a lot recently due to his source code analysis” and ”described to us the process by which a command string is generated for the Instron testing device.” Shawn tends to work alone (I observe this on a number of occasions) and then relate his finished work or findings to his teammates.

The sociogram for the team at this point illustrates the increasing importance of the sub-sponsor, who is now located closer to the team than the sponsor (Figure 6.15). Additionally, the team now relies on mentors, though most of these (observed) connections are through Shawn, who considers them to be potentially useful but generally reports frustration when reporting back on a meeting. This is contrasted with Colin’s perceptions of the mentor, which are high and in whom he places much hope whenever the team is faced with an unknown. Shawn is more realistic about what these mentors can or will do for them. This trend continues throughout the semester.

Menaka is now moved closer to the team, though her role may not always be consequential to the team’s progress in negotiating the impasse, she contributes much towards completing course goals. Todd, on the other hand, is still located further from the others, based on his comments on surveys and observations of interactions, in which he physically positions himself apart from the team.

Shawn and Colin continue to the ones who primarily address the TA at weekly meetings, though there is tension between them. This timepoint has the highest Cohesion in scores of any of the times.

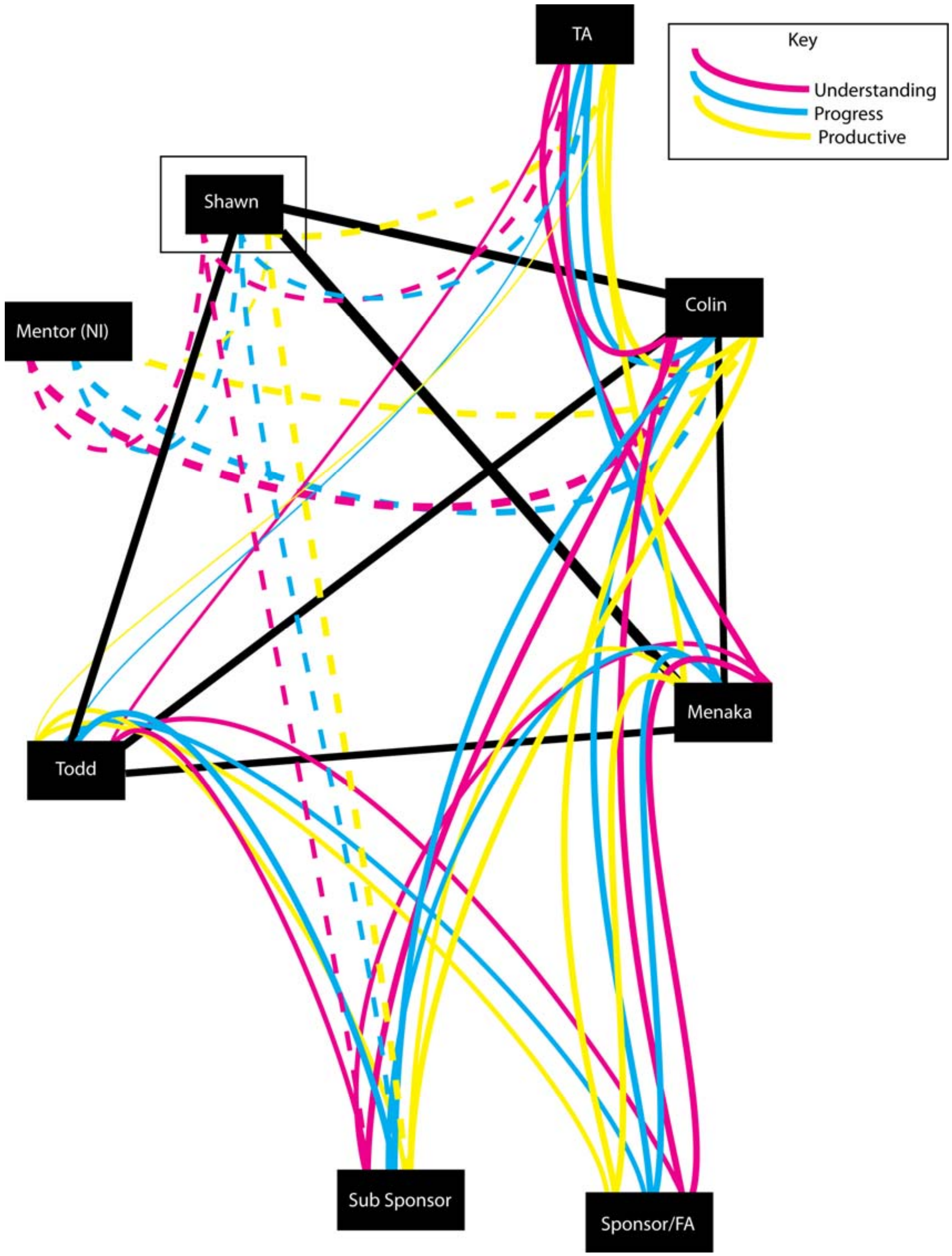

Figure 6.15. Sociogram of team 3.2 from March

At the last meeting, there was a clear and pressing interest to talk to a mentor at NI. However, at the March 20th weekly meeting, when Shawn talks about this latest interaction with NI, it appears not to have been particularly fruitful. Additionally, though Colin indicated his intent to come along, this has not happened, though it is not clear why. This seems to be a recurrent issue, that Colin plans to but does not actually interact with their mentors. As a result, Shawn effectively has an additional design team of experts that he leverages, though he recognizes their limitations:

Shawn: He said that uh, our progress was good. […] The problem that he thinks we're having now is […] some disparity between the high level C code and what's actually getting hooked through the serial port, so he suggested that we, um, uh, try to send a message that we know. […] Basically what we tried to do before. […] He also suggested that we might wanna look into- or that we should look at- try and find the actual Palm library and figure out what it does. […] I'm not sure how much I agree, I mean, granted he is the superior authority here but it-it seemed to me that with the library documentation that pretty much already says what the code does and when you set parameters for serial things you should get reproducible results of… I don't know how much we could really gain by looking for the serial API but at the same time there's a road block so.

Colin: He didn't give any pointers for LabVIEW.

Shawn: No. […] he didn't know about voltages like what is high and low what should be, what the serial port does. Said he thinks the serial port just goes from zero to three anyway so it should match up, but then I don't know what our problem is so- and then I took a break for a week and didn't think about it. That's pretty much…

Sanjay: Okay. Soooo.

Shawn: It wasn't as helpful as I had hoped.

Sanjay: So, it kind of puts you back where you were before the meeting.

Shawn: Yeah.

Sanjay: I'm not sure you gathered any more information from the meeting.

Shawn: Yeah. I mean it seemed so at the time and then on the drive home, I was, you know, it happens, come up with questions after it's over. Just didn't think about them then. Basically the guys l talked to didn't know low level stuff. They don't know about writing drivers or anything like that so if, if it turns out that that's what we need to do, we need get transferred again.

Colin: Is there someone else there who knows more about that?

Shawn: Yeah I wrote down a suggestion. There weren't many. Um, yeah, he suggested [reading from journal] look at the API itself, try and figure out what's going on there, and to try sending single bytes from the PDA to the Instron which you can't really do because you don't, we can't change that code so I don't really know how to do that.

This exchange again highlights the differing expectations Shawn and Colin have for their mentors at NI, in part because of the very different problem spaces they see. Because Shawn has a fuller understanding of the problem, he seeks out more specific information than Colin, who is not sure where the impasse really lies. Sanjay is concerned about their progress and suggests they begin working on the tedious solution (Shawn's "Bad Idea!"), but Shawn does not entertain this idea. He instead lists out the possible solutions, one of which will turn out to be their final solution path, though they do not investigate it for some time yet. He is determined to understand why it is not working, adopting a practical approach to a relatively theoretical problem (at least in terms of his understanding of it) rather than accepting the tedious but somewhat more practical solution. This will ultimately be beneficial, but likely is more time consuming than the "tedious" solution:

Sanjay: Okay, so what are you guys gonna do next? It almost seems like you should just go ahead and convert code into LabVIEW. It seems like the most tedious, but at least it seems like progress. […] Just rewrite everything.

Shawn: Yeah but- but the problem is, so given that we have some, like the four things that are sent for initiation and we can- there's a command that we can change the status of the LEDs, um, there, I mean, it's one of two things. Either I'm translating it wrong which is totally possible. I could just be misreading it, um, or there's something just wrong with the way we're talking to it in the, in the voltages or the, or I don't really know what else. […] It's pretty like straightforward in the way it's done. I may have, I might have it. I mean it can't be reversed, it's, I don't know. I don't know what could be different. Which sucks.

Colin suggests that they get more time with people at NI and bring the device with them, and Shawn agrees with this idea. Sanjay suggests that they try to find someone at NI with the expertise they need, to which Shawn replies: "I was kinda planning on doing that just, I, I wanted to try and figure out what direction we needed to go before I just said

'Is there anyone else we could talk to?' 'cause if we have an idea of who we need to talk to or what expertise." Concerned about his team, Sanjay brings up their issues at the April 1st meeting between the TAs and the professor:

Sanjay: Their project appears to have hit a wall. I guess that's the best way to say it. They, uh, so, they, so if you remember from the presentation they were trying to take the source code from the Palm OS and convert it to something they can use for LabVIEW and they're just stuck. I mean there's really no other way to put it. They, I wouldn't say they're not trying -they're trying to get in contact with NI but they haven't been able to do that, um. I'm, here, I'm really not sure where they're supposed to go. Where they are right now, they don't have much expertise in Palm OS code or anything like that. I told them to download the Palm OS library to see if they can use that to, uh, with, for non Windows to see if they can kind of manipulate code- some of the code- but I that's last week's meeting. I haven't met with them yet this week to see where they are. It's like, right now they, they're far away from their ultimate goal. […]

Dr. Davies: So what their need is- is to get some resources they don't have? […] Do they have a good contact at NI?

Sanjay: So, they have, they've been kind of being bounced around, from what they've told me. They had an initial contact who helped them a little bit and then told them he doesn't really know what they need, so moved 'em on to a different guy who helped them a little, but, but apparently has exhausted his resources and now they're trying to find someone else.

Brian, the sub-sponsor who has also been mentoring the team, is present and speaks for the sponsor to some degree. He highlights that a negative finding would still be useful, and speaks about the needed iteration in projects such as this, but Sanjay is concerned about his teams' morale if they cannot make progress on a solution:

Brian: I think we'll be happy with just progress, if we can, I mean, it may end up- when we first started talking to NI, the guy I started talking to said if we can't get this, we'll probably end up just having to build a material tester from scratch that can run on LabVIEW. He got kind of excited about that so if at the conclusion of this semester the whole thing is, we tried this avenue and it's gonna be a dead end, pass it on to the next team, let's build on it. […]

Sanjay: I'm just a little worried that they feel like, I think they're just really frustrated right now.

Brian: No, it's science.
Sanjay: [laughs] Yeah. No.
Brian: You don't get success from the first.
Sanjay: No, exactly.
Brian: Play all the time and we know that if the conclusion is 'we tried this and it doesn't work' then we've learned something and can drive on from there.

This suggestion that a negative finding would still be useful for the sponsor is interesting in its authenticity, but quite different from what many students experience in their coursework. Sanjay is concerned that if they cannot make progress, they will simply see it as a failure, not as contributing useful information. Though he relates this to the team, it turns out that Shawn has ruled out many other problems, and this has left him with a likely solution path. At the April 3rd weekly meeting, Shawn reports that they have a possible explanation for the problems they have been having:

Shawn: Turns out we were looking at the voltages wrong.
Sanjay: Okay?
Shawn: We were looking, we were assuming that the high voltage was logical zero and low voltage was logical one, which isn't the case. If we look at it the other way around, the way-
Sanjay: You know, I actually thought that while I was reading your design review, I was like, 'that's backwards.' […]
Shawn: And so if we read each byte up as we went down in the series of bytes, we got the commands we expected.
Sanjay: Okay! So that's great!

Despite this news, Sanjay also reassures the team that even if they show that it won't work, negative findings are also progress:

Sanjay: Talked in our TA meeting about it and talked to Brian and he just, if you can't get anything done like, like looks like you are making really good progress, but if the end of road is, this is just not an avenue that is gonna work, that you're not gonna be able to translate the PDA code, well, I mean that's fine, I mean that's where you guys stop.

The team feels recharged now that they have a possible solution and respond to Sanjay's encouragement with confidence. Shawn, however, who can see the fuller scope of the problem space, is aware of how much work they still have to do and expresses less optimism:

Colin: I don't know if that will be the case.
Menaka: Yeah, I think, that was like last week.
Sanjay: Don't be like, 'Oh, I'm free,' but, uh, [laughter] I'm saying like, don't be like, be hard on yourselves or anything.
Shawn: Okay.
Colin: I think it's gonna work. How much of it, I think it's likely we're gonna finish this before the end of the semester.
Shawn: At least some portion of it we can show.. I just want..
Menaka: We need like communication.
Shawn: Right, yeah, no. One thing I don't think we've looked at, like, I haven't looked at all, is, uh, how the data receiving works, like when you have, yeah, when the Instron runs its test, you hit a button on the Instron and it just starts pumping data back so there's a specific kinda data report, I mean it's asynchronous, right? It doesn't need prompting.
Sanjay: Yeah.
Shawn: So figure out how that works. 'Cause right now we're only working on talking to it synchronously. I send a command.
Sanjay: Yeah.
Shawn: You tell me you got it so the actual testing part could, could very well be really hard.

The differences in how Colin and Menaka respond versus how Shawn responds serves to highlight how much he has sheltered them from seeing the same problem space that he sees. Rather, he delegates subtasks, generally with specifics about how they should be accomplished.

After this exchange they make plans for purchasing a voltage converter. Shawn brings up a web page with various options and explains the pros and cons of each type and why he thinks they should order a specific converter. Colin decides they should buy it locally and places a phone call to find out if a local store carries the part they need, but quickly passes the phone to Shawn because only Shawn can explain what it is that they need. Colin's notebook reads "we need some sort of converter" whereas Shawn's notebook includes details about the part number and functionality of it.

At the April 17th weekly meeting the team reports that the voltage converter has arrived and has allowed them to make tremendous progress:

Shawn: This just converts them to the appropriate range. […] That's all it took really, uh and once we had that it turned out that everything we had was right, it was just the wrong voltages.

Though they have overcome the major impasse of their project, there is yet much work to be done. When Sanjay leaves, Shawn spends half an hour explaining what remains to be done and how it should be done, not specifically delegating tasks, but laying them out for his teammates to take.

In the sociogram (Figure 6.15) from this point in the team's progress, the sponsor is located more distally and the sub-sponsor is closer, representing the shift in focus that was observed; this shift is reflected in the interaction between the TA and the sub-sponsor, who explains his goals for the project, and in the team's willingness to discard an aspect of the project that pertained to using the device in a classroom as opposed to research setting.

The team is still somewhat more Cohesive in their scores they give, as compared to the first time point. Shawn is still located slightly apart from the team, indicating his unwillingness to let others into the problem space with him. He is located closer to the mentor than to his team mates, illustrating his respect for the mentor expertise even when it is not directly helpful.

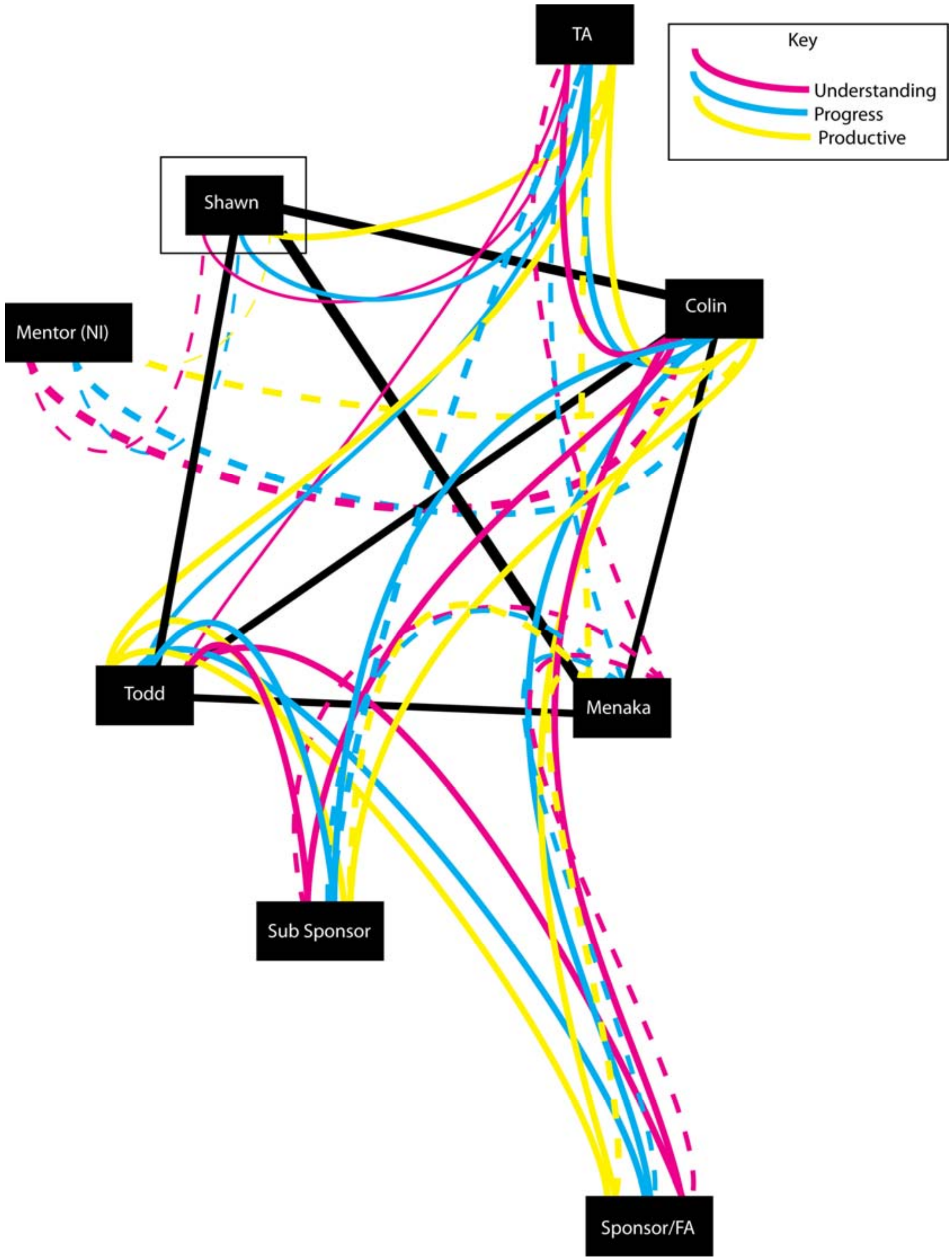

Figure 6.16. Sociogram of team 3.2 from late April

The team presents their final design on April 28th to their sponsor, TA, and the course professor. All are aware that just three weeks prior, the design seemed impossible. Though they have not finished all hoped for tasks, they have overcome a significant challenge. When the course instructor asks them how they overcame the impasse ("How did you crack the code?"), Shawn explains:

Shawn: A lot of long nights. But, uh, eventually, uh, honestly I just got fed up with the, with not being able to plug the cable into the other end into the computer. What's wrong? What could possibly be wrong? We have the bits in order, we have everything the way it's supposed to be, the way it is and so I just hooked up the PC to the elvis board and looked at the voltages and suddenly realized they were not our friendly ttl voltages but RS232 voltages so the next day we ordered a converter.

Experts ranked their initial work as having low Innovation and Efficiency at an early point (three out of five on each) but higher by their final design with a four on Efficiency and a five on Innovation. The Cohesion for this team more closely parallels the class as a whole (Figure 6.17), generally increasing throughout the course of the project.

On May 2nd, Menaka makes a final entry in her design journal as follows: "This project had a lot of EE/programming focus, so I had to learn a lot of new things in order to complete it- soldering, wire manipulation, LabVIEW, etc. I definitely had the least experience, but was able to learn a lot. It feels nice to have accomplished our goals for this semester and to have created something."

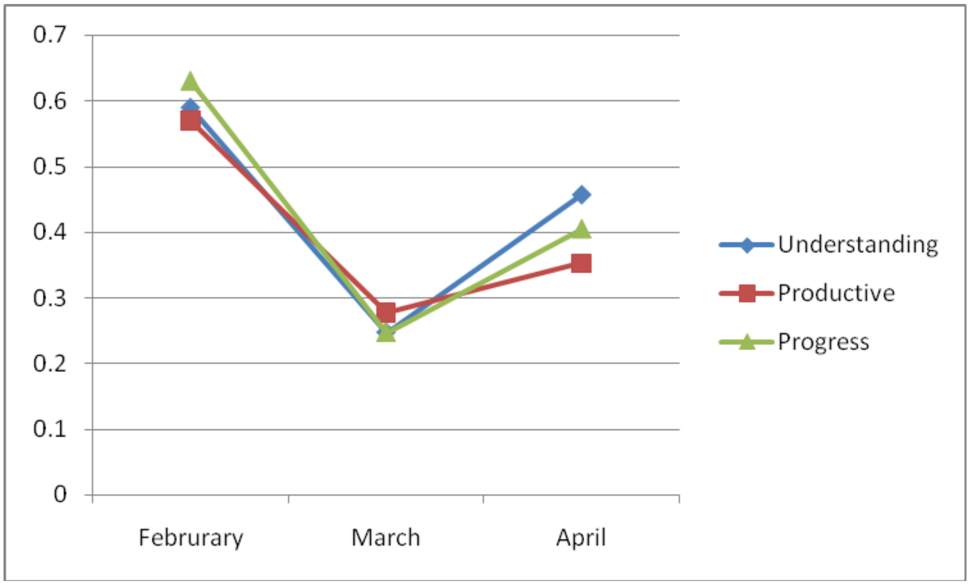

Figure 6.17. Team cohesion over the spring semester

Team 3.4

Team 3.4 is a four member team with three native English speakers: Bob and Steve, both Caucasian men, Dillon, a Vietnamese American man who prefers to go by his "nickname" rather than his given name which is Vietnamese, and Daniela, a native Spanish speaking Mexican American. Their TA is Michelle, a Vietnamese American woman. Their Faculty Advisor is from BME and holds an MD.

Their project is to specify sensors and evaluate them for detecting and monitoring specific biochemical processes in the body. Their sponsor, Dr. Jackson, the director of a local biomedical technology company, is one of the few that contributes several projects each year, but he delegates mentorship to specific people (such as Dr. Hansen) within his company. His projects are often innovative or exploratory, and his standards are very high.

As with the prior case study teams, the design impasse emerges roughly three months into the project (Figure 6.18). This team's impasse centers on relationships with mentors and a struggle to find a design component to what could otherwise appear to be a life sciences project.

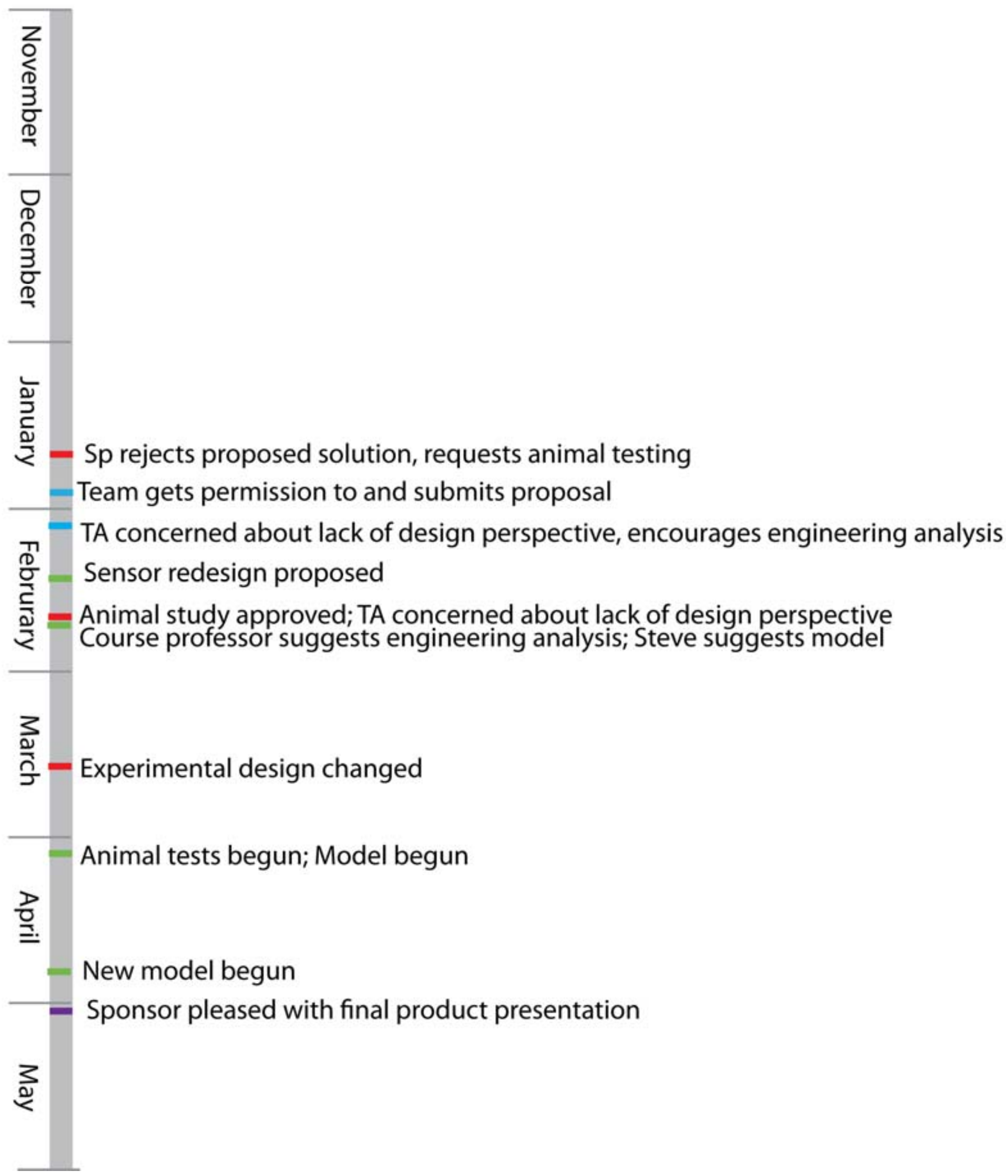

Figure 6.18. Timeline of the impasse of team 3.4

Origins of an Impasse: Science and Engineering Perspectives

The origins of the impasse in this case are that science perspectives have been privileged over design perspectives. In this case, this issue is driven by both the teams' prior preparation as well as the nature of the design project they have been given. The project could have been given to a team of biologists as a life sciences project, and the team struggles to find a design perspective in the process, perhaps because they have had more experience in laboratory settings than in design studio settings.

Negotiating an Impasse: Locating Expertise

Team 3.4 distribute and negotiate their tasks. Their receptivity to ideas depends much on from whom the idea comes and what the idea is about. They accept ideas from those they perceive to be experts, but not from their teaching assistant. The team leader, Steve, is receptive to ideas that will move them towards accomplishing their goal of performing animal surgeries, but is not receptive to ideas that move them towards design perspectives. Likewise with apprenticeship, they teach each other about the surgeries for practical reasons, but otherwise do not much engage in apprenticeship within the team.

Another theme that emerges is the role of experts and expertise. Instead of inviting peers and proximal mentors (graduate students, TA) into the problem space, the team seeks out the highest expertise they can find. They value expertise, but do not incorporate it initially, except to justify basic decisions, making them something akin to Searle's (1980) Chinese Room: As a system, they make expert-like decisions, but do not understand the reason for these decisions.

Team 3.4 and the Missing Design

In mid-January, this team receives feedback about their proposed design plan from their sponsor. They are confused because the comments do not seem to relate to conversations they have had with Dr. Hansen, their sponsor. The comments indicate that animal testing will be needed, rather than their proposed sensor design. Their TA, Michelle, brings this issue up at her next meeting with the course professor and other TAs (Jan. 22nd), explaining that the feedback they got from the sponsor was unexpected. What the sponsor really seems to want is for the team to demonstrate through animal testing whether or not it would be feasible to place an existing externally-used sensor internally to monitor chemical changes related to a medical condition. When Michelle explains this, the professor is skeptical because there is a "huge lead time" needed because of approval for such studies, and he tells her to encourage them to talk to the head of the animal studies lab where he believes they will be told the "possibility is zero."

At this meeting, Michelle also relates the team's confusion about the response from the sponsor, and the course instructor explains that the there are two people involved: the Head Sponsor, Dr. Jackson, does not interact with the teams but does he comes up with the problems; and the primary contact, Dr. Hansen, has been given the job of overseeing the team, and conveying Dr. Jackson's vision, but this has not happened.

During the January 28th weekly meeting, the team talks about writing the proposal for conducting animal studies, a prospect that excites them because two of them have experience working in animal labs. They discuss the need for a hypothesis, referencing their faculty advisor who is guiding them through the application process. Michelle encourages them to talk to experts in the department about the realistic timeline of their project and to prepare their sponsor for the fact that if anything goes wrong, they will have nothing, but Steve and Bob are adamant that this is ”the only option,” and “the only thing [they] should be doing.” Towards the end of the meeting, Michelle gives them advice about the head sponsor, Dr. Jackson, warning them that his comments should be taken “with a grain of salt,” and finally revealing that the comments that had so troubled them were Dr. Jackson, not Dr. Hansen as they had believed. Steve voices the surprise apparent on the team's faces: “Oh! I had no idea. That makes sense.”

The sociogram representing their interactions at this time includes dashed lines to represent observed but not reported interactions (Figure 6.19). Contrasted with the prior cases, the sponsors occupy the top of the sociogram to represent the top down role the sponsors play in this project. The faculty advisor is placed close to Steve, who has worked in his lab. Steve is respectful of his faculty advisor, but does not appreciate the teaching assistant, Michelle, who is placed opposite Steve, and though a close rapport does not develop between Daniela and Michelle, they often sit next to one another. At this point, the teammates appear to be amicable with each other during meetings, and to not have any particular alliances or established working patterns, in terms of who works with whom on sub tasks, as I observed in other teams.

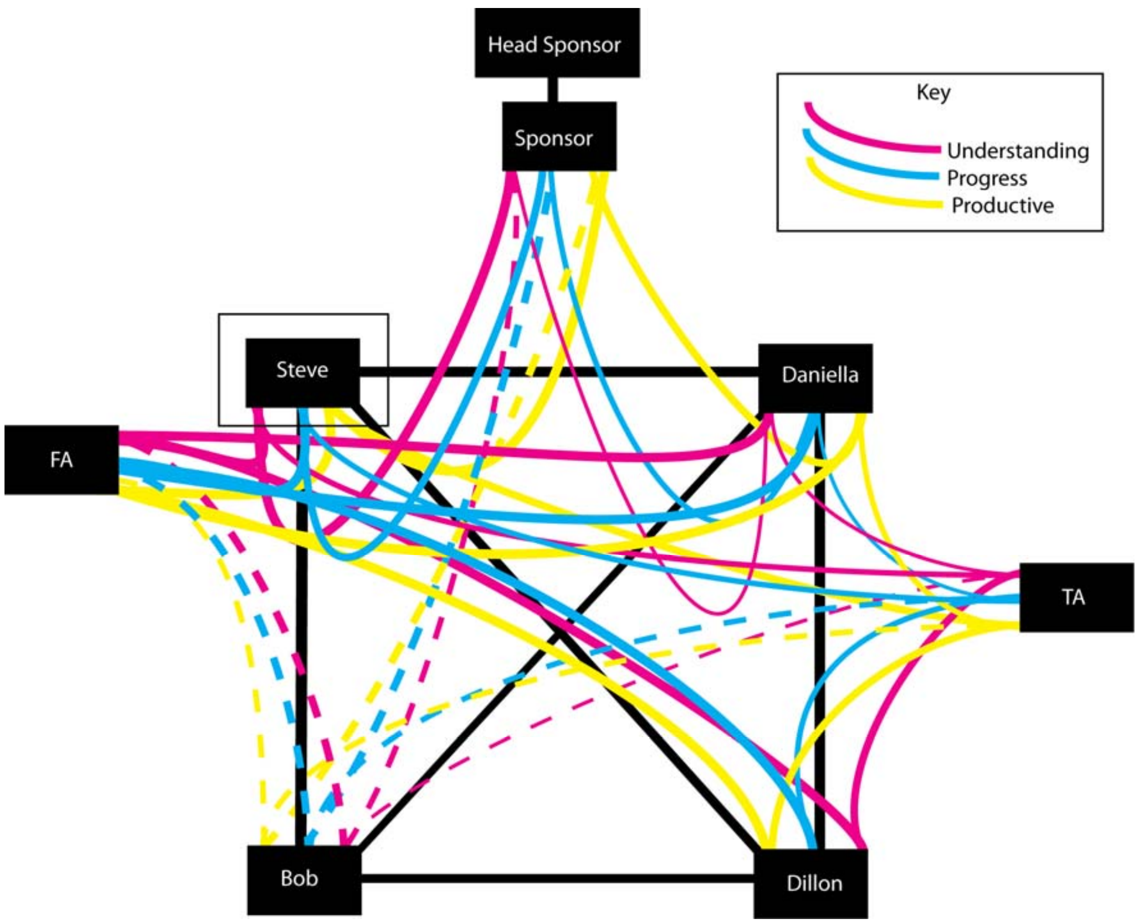

Figure 6.19. Sociogram of team 3.4 from early February

At the meeting with the course professor the next day, Michelle reports that they have gotten approval to submit an animal study, meaning that they will probably get approval for the study. She and the professor both feel strongly that they need a back-up plan.

During the February 4th weekly meeting between the team and the TA, it has become increasingly apparent that the team is not designing anything and thus, Michelle stresses the need for engineering analysis:

Michelle: Try to have some kind of engineering analysis on, like, kind of try to guess what your data's gonna look like, and how you're gonna analyze it. Um, what you want it to look like. What the CO_2 levels should be and, um, what you expect in the stomach. And I think you should, um, in your case um it would be good already to kind of have a back-up plan. I'm gonna ask. [They all write in their design journals].

Science perspectives are privileged over design perspectives in this team. Though they have a project that could be treated as a science problem, they are in a design class and are urged to adopt a design/engineering perspective. Michelle pushes them to connect what they are doing to customer needs as a way to frame what is otherwise a biomedical project as an engineering design project, but the team focuses on how novel it is rather than why it is needed:

Michelle: Why is your project so great? Another question I'm gonna ask again.
Steve: Well, I mean, it's never been done! I mean what we're trying to do-it's, nobody’s done it!

Michelle pushes them to explain the customer needs, which should be the basis for the design, then asks for clarification of their planned use of the sensor. Steve explains that it would be used during surgery, and this brings out a question, hesitantly posed by Daniela, that is then dismissed as not part of the scope of their problem. Daniela actually poses the question to Michelle, turning to face her and speaking to her as she brings up this dissonant perspective. This exchange again highlights how the team perceives their project to be about science rather than design. The disagreement over how the sensor will be used also demonstrates that the team does not really have a shared understanding of the project at this point. This is also reflected in a survey they complete at this time, in which they answer: “using an idea that has produced nothing but commercial failures to produce a marketable product” and “I'm not satisfied with the benefit our project can provide patients.”

Daniela: I just, um, something bothers me. The fact that we are putting the sensor on the stomach during surgery, but then we're gonna, the surgery only lasts one to two hours and we're gonna take it off and the patient is gonna be, well, the surgery is gonna be over and there's not gonna be any monitoring afterwards, and I'm thinking well, there's higher chance of sepsis, I mean shock, afterwards, right? So, should we think about leaving the sensor, or… cause I don't really?
Dillon: Seriously, that could be, like, the next project.
Steve: Yeah, I think that, like are you talking about in real life? Like?
Daniela: Yeah, like, so using it.

This somewhat troubling exchange highlights tension in the team and shows the how the team struggles to adopt a design perspective. Furthermore, Steve’s question about how the device would be used (“Are you talking about in real life?) not only challenges the design perspective Daniela attempts to adopt, but also demonstrates a disconnect in perspective; Steve frames this as a school problem even thought they are being asked to solve a real-world problem. The response Daniela gets from her team mates seems like an attack, but Daniela does not appear to take it personally, though whenever she poses these dissenting design ideas, she tends turn her body towards Michelle and to speak facing Michelle, as if this is how she gains voice. This defensiveness is likely a response to the push to adopt the less familiar and less comfortable design perspective. As they continue this conversation, it becomes increasingly clear that there is a lack of agreement about what they are doing. They retreat into an explanation of what they are “supposed” to be doing, though in a design problem, they should be more in control of this than they appear to be, which could be attributed to the negative response they got on their design proposal:

Bob: I thought the project was to do an internal sensor that you left in?
Daniela: So we are gonna?
Steve: I think that that's, be-
Daniela: How long are we gonna leave…? […]
Bob: I'm not sure, uh.
Steve: I think that would be something left up to surgeon or something, honestly likelikelike, our project, I think it's kinda outside the scope of our project.
Bob: If we left it up to the surgeon and whoever actually designs the sensor.
Steve: Yeah, whoever is really doing this.
Bob: 'Cause we're not supposed to be designing anything.
Steve: Yeah, we're just seeing if you can do it. We just have two types of sensors and we're gonna see if we can do it we're gonna see if a shock patient whether or not the CO_2 levels can be measured or change to a degree that we, they show up, or the…
Bob: Using currently available sensors.
Daniela: I don't even know if it's okay to just leave it there.
Steve: It's all right.
Daniela: These are, I mean, sort of, days?
Dillon: They're not gonna want to cut them open again and just take it out.
Bob: When they do open abdomen, though, they also do, um, basically a screen for a while.
Dillon: Yeah, but after?
Bob: You have the patients coming back even days after.
Steve: I don't know.
Daniela: I keep thinking about what Dr. Roberts [the faculty advisor] said, like, if we implanted in the uterus or bladder, I'm thinking that's more feasible than what you're talking about.
Steve: Right.
Michelle: So, okay now I'm like really confused-[Steve laughs] um so you're testing basically, um, whatever testing you're gonna do on the animal, it's one kind of like what a doctor would do on like on an open abdomen surgery right?
Steve: Yeah.

This exchange has highlighted their lack of design perspective in terms of the missing customer perspective. They frame this problem as a science problem, and therefore have a goal to understand how the sensor functions and how it will measure CO_2, but they have not considered whether using it would be feasible or how doctors' and patients' needs should drive their exploration of the problem space. Daniela attempts to introduce a design perspective, but her ideas are not taken up by the team. When she brings up the idea of using the bladder or uterus for feasibility reasons (as both are accessible without incisions) the team eventually discounts the bladder for valid reasons (the pH would interfere with the sensor), they never bother to consider the uterus.

As the conversation continues, they reference their mentors, a common strategy for this team. They seek out mentors beyond those required by the course, perhaps in part because they lack confidence in their TA, demonstrated in a survey completed at this time, in which they all state that Michelle does not have relevant expertise for their project. Steve is a charismatic and enthusiastic young man and enlists help from many people and is adept at identifying expertise in others and convincing such people to help. Here, he describes his plan, which he ultimately carries out exactly as stated.

Michelle: Okay, so you'll be doing that yourselves?
Dillon: Dr. Roberts has to be there.
Steve: Yeah, so Dr. Roberts will be there and then there's a guy, yeah, there's just some other people- we'll probably be able to get a little group of three or four people plus us, people that'll help us, people that really have a lot of experience with this kind of stuff.

This provides an interesting contrast to how he next responds when Michelle continues to push the team towards adopting a design perspective. Michelle seems unsure how to explain what this would mean. She rephrases and hedges as she explains, and it is not surprising that her team is uncertain what she means:

Michelle: I'm just, I'm just going to say this, this is honestly kind of what I think from seeing this but I think that by just evaluating the CO_2 levels, I'm not sure how much of engineering analysis that is. Do you know what I mean? I can see how it's like biomedical related and all that but I don't see any like hard core engineering.

Steve: Well, I think that that would only come from comparing the two sensors right, I mean that's why we have two sensors. Just to put one in there you answer a yes or no question: can it work? But with two and changing locations and then the way that they work. That's all I got. [laughter]

Michelle: Like, I don't know if there's some kind of like equation? And correlating, like CO_2 to something else, because then at least it's a little bit more analysis rather than compare some method kind of statistical. You know what I mean? […]

Steve: Yeah, I mean, but you know- not to be disrespectful by any means- but that's the project. I mean that's what it is. The whole point of our project is to describe the merits and disadvantages of CO_2 sensors to detect. […] I think, I mean, I think to be honest, a fair enough argument against that is the simple fact that we're the only group that's even attempted to do this to get animal research, to get animals and in my opinion or I personally, what I want to do you know, to go to graduate school and continue doing this kind of stuff, like it's a good thing to learn how to go through the proposal process and learn those things, and I think that I think that just last week, I learned a lot more than 99% of the kids in this class. You know nobody else has done it And so I think that that may not be the engineering analysis but I think that it's a hard core task to take on.

Michelle: [hesitantly] Ye-ah. I mean, yeah. I do think that you guys have kind of gone a long way for it only being February but you know, keep in mind that this is design class.

Steve has constructed a scientific problem space that he is excited about and that will answer the scientific problem, but not a design space. This space is not necessarily preferred by all, and this is reflected as Daniela and Bob once again question the project:

Bob: Well, this project is definitely nothing like the hard-core engineering I thought engineering would be like, where you go and designing a machine to go through those or doing material analysis but this is a lot more like a bioinformatics problem with the evaluation method doing statistical analysis of various sensors correlating how they work. […]

Daniela: It's not really, we're not designing it, I mean, anything. It would be more design if we had to design the sensor which I thought we were gonna have to do but he didn't want, the company doesn't want us to.

Finally Daniela has an ally also questioning what they are doing. This critical mass results in a possible redesign direction. Though Michelle has struggled to put into words what a design perspective would be like for their project, she recognizes it once it is posited:

Dillon: Might have to design modifications to the transcutaneous sensor ‘cause it's meant to be placed on the skin. I don't know if we could place it inside without causing adverse reactions.
Michelle: There you go. There's the engineering analysis.

Michelle then brings up another issue that continues to trouble the team. Although they are adept at locating expertise, they tend to leave it in the expert. They seek out mentors and assistance, but allow those mentors to make decisions for them without expressing understanding for the reasoning behind the decision. Steve in particular places a high value on expertise, and tends to accept it uncritically. His willingness to be critical of Michelle may stem from his perception of her as not having relevant expertise. When Michelle requests further explanation from him about why they are using the stomach as opposed to, as Daniela brought up, the bladder or uterus, it seems that this design direction was not a decision. She advises them to “Try not to, like, say ‘well our sponsor wanted it in the stomach.’ You have to find like a better argument for that. […] Do not say ‘our sponsor told us to do this.’”

At the TA meeting the next day, Michelle voices her concerns to the course professor, both about how the team is doing in terms of design and how they have become defensive towards her. He asks her to let them know that he agrees “with her concerns” and that the sponsor will “require a real sense of technical rigor.”

One week later (Feb. 11th), during an interim presentation, the team explains their back-up plan in case their proposal for testing is rejected; it is essentially to find a commercial lab and run the tests, but not to change what they are doing. Steve again emphasizes the novel nature of what they are doing: “See, now the very hard thing about this is there's no data. Nobody has done this. There's zero data for what we're trying to do.”

They have now included plans to redesign the sensor but when Michelle questions them about this, she becomes concerned that this will be very easy to accomplish and may not be enough to be considered design. She suggests that they consider designing software instead, or more functionally redesigning a sensor, but is met with frustration as the students explain that this was their initial design plan but it was rejected by the sponsor. They explore the idea of designing software:

Daniela: We proposed that to the sponsor but he didn't like that idea.
Steve: Yeah he doesn't want us to try to construct-
Daniela: He told us we could do it.
Dillon: We would have to develop the algorithms just to, like, get the data into something readable.
Steve: I mean, it would be doable. We'd have to recruit the help of a lot of other people in terms of signal analysis.

Daniela's attempts to instill in the team more of a design direction seem to have finally been heard; at least now, with Michelle pushing as well, they are entertaining these thoughts. Steve suggests the need for mentorship, a strategy he seems to be very successful with. Michelle continues to push them towards a design perspective:

Michelle: You have to remember how you talked about all the technical aspects. I mean, most groups are having that problem anyway and I think. Like, that would be a good project for this class.
Steve: A grade.
Michelle: I mean, if that's not what he wants-
Bob: The sponsor said 'no.' He doesn't even want us to try.

Steve's comment again reflects the lack of authenticity he feels about this project. Because he has firmly adopted a science perspective, he has begun to see the design aspect as unnecessary or busy work, particularly as this does not seem to be what the sponsor would like. Michelle struggles to find a way to help her team to find a relevant design perspective, and is still concerned about the direction the project is taking because she knows their plans depend a great deal on timing working out just right:

Michelle: At the same time, he wants you to do all these things that might not work. [She is referring to animal testing and to the very expensive sensors they are attempting to lease.] […]
Steve: I was hoping we would find out before we met with you today so we would have, like, but we should find out by Thursday, I imagine, at the latest.
Michelle: But even then, like, how long is it going to take you to find out if you get these and how long is it going to take for you to actually have them come in?
Steve: I don't, I definitely agree. I mean, we, we're uh, making progress as we go, like Daniela has been talking to all the people regarding sensors. If [the proposal] goes through we should be able to start. In terms of a time frame, I don't think we're going to experience too much of a time crunch.

When Michelle asks Steve to explain how they chose the number of animals, Steve again relies on expert answers without incorporating the expertise, again reflecting a rather uncritical approach to expertise:

Steve: Honestly, like, I talked to the guy to whom we're supposed to submit these proposals. I talked to him and when there's no previous data and no data that's been around that you can use, what you do is, they have actually written in all of the bylaws, that it comes from expertise, so Dr. Roberts, from his suggestion that Dr. Roberts and Dr. Orr who runs the animal resources center told us, eight rats per sensor, so that's relevant in its own right from expert-
Michelle: Right, but I mean it would?
Steve: That's how they do it, that's, I mean when there's no data you can't, you can't come up with statistics if you don't have any data.

This trend of simply citing expertise rather than the reasoning behind an expert's judgment recurs in later conversations. Michelle is concerned about this but unsure how to address it.

Before Michelle arrives for the February 18th weekly meeting, the team relates to me that they have gotten approval for their animal study. Before recording, they relate to me that when they told Michelle on Friday, she seemed "unenthused." They ask me if any other group has ever gotten such approval. I tell them no. They complain about Michelle. When she arrives, they confront her about their grade on a recent assignment. Michelle has tried to convey some of her concerns about the lack of design perspective through a lower grade. This is ambiguous and Steve finally questions why this project was approved for the design course:

Steve: You thought that our, that our progress that we had made was minimal and you felt that our analysis was minimal. I think that, I mean, I just think that it's been kind of taken out of context because it's not the classical way this course normally goes. I mean, I don't know, I think that we've achieved quite a bit personally. I think that we, I mean when we spoke with our sponsor on Friday and told him we got approval he freaked out he was, like, 'I hope you all are toasting right now because, like, that doesn't happen. Undergrads don't get approval' so-

Michelle: Okay, so um, you obviously know about the main concern that I had, was it wasn't technical. And that, and that basically goes along with what you just said, how you're project is been following- how this course usually does but that's the whole concept of this course.

Steve: But why did? Why was a project like this accepted?

Michelle: I think because it assumed that you would, um, from what I think, from when I read your [statement of work], um, they assume that you would be building your own sensor but from what you're proposing, from, me, you're just taking kind of like all these commercial products and then testing your CO_2 and then I can see how it can become, um, more technical if you did some statistical analysis on that but then the only thing is you have 8 animals. It's like all of that is there, everything is there, but you're missing a small part but that small part is what Dr. Davies is going to grade you on.

Steve: I gotcha. But if the desire is not there for us to construct a sensor, what are we supposed to do?

Michelle: You should talk to Dr. Davies. […] I think people tend to forget that there's two people you have to make happy- like, one your sponsor and other the Dr. Davies.

This conversation encapsulates this team's impasse as well as how they negotiate it, by seeking and using mentors. Including the course instructor among their mentors turns out to be what helps them shift from simply seeing design as busy work to seeing it as a meaningful and relevant contribution.

Michelle had critiqued them for not explaining how they decided on using eight animals, and Steve defends the choice, again highlighting how adept he is at finding expertise, yet not incorporating it. When Michelle pushes for explanation and even tries to rephrase her question, Steve becomes immediately defensive, and I decide to step in to reframe the question:

Steve: You wanted to know where we got those numbers for the rats and I think that you took that as like defensiveness but in reality, like, the USDA- they say if there's no previous data, that's acceptable for a professional to recommend a number.
Michelle: Well, 'cause I talked to somebody else and she, she gave me a reason why they used eight, so and I'm still kind of waiting for you guys to figure that out. […]
Steve: I mean, I was shown literally verbatim, word for word, by the guy who's in charge of [the group running animal labs] who is the liaison between [the lab] and researchers and he showed me if there is no statistical data available then they report recommendations without say, decades and decades of animal research experience.
Vanessa: Can you, can you get them to explain why *they* would use that number? […]
Steve: Yeah, and I mean, I totally agree with that with, like why eight? Or why?
Vanessa: Why the expert would say eight?
Steve: Because I think it allows for enough variation in there, I think it allows for variation if you're gonna have, it's a relatively arbitrary number but it's, I mean if you had four, I mean, that's not gonna be enough if one of them is way off the charts in another direction, then that's gonna statistically mess up, and so eight I think falls into some sort of acceptable range. I mean, I don't have a wonderful explanation for that.
Michelle: No, that's exactly what I was looking for!
Steve: O-oh! […]
Michelle: But I wanted to make sure that you were, um, you weren't just taking up what people were telling you.

This conversation turns out to be pivotal. Henceforth, Michelle frames these probing questions as what the expert would think ("But do you know why he would want that, like, from a surgeon's point of view?"). This different framing allows the team to practice multiple perspective taking as they attempt to explain the expert reasoning. This is an important aspect of their learning in the project, but they still lack an engineering perspective. This is what Michelle brings up next, but Steve is defensive about their project.

Steve: The whole senior design course was worth it to me because we went through this process where something, I'm gonna be doing time and time and time again.

Michelle: Well I mean when, when I did my design courses nobody had previous knowledge and I think that's why the course is supposed to be a year long, so it takes more than a semester and then you, you know, you work in groups and also that's just a little less work, um, and I'm, I'm glad that you already have, um, have this experience from it, but again it's like a different type of experience than like some of the faculty are gonna look for.

Steve: Yeah, yeah.

Michelle: Because I mean, like, getting all this, for all we know, you could just be *really resourceful* but we don't know if that makes you, like, a good engineer.

In this exchange, Michelle struggles to explain why their missing design perspective is a problem. She has identified them as being resourceful, skillful at locating resources and mentors to do things that they are not able to do themselves. Unlike team 3.2, they do not leverage these resources to create an apprenticeship system.

Steve, in particular, does not seem to have ownership of the problem space, as indicated by his comments about the project:

Steve: It's just my biggest, my biggest frustration with this is just, like this, like this is the project, like *this is the project we were given*. I mean if, if like Dr. Davies, and I don't mean to be disrespectful, I mean, if somebody didn't want us to do this project it shouldn't have been accepted. It shouldn't have been given to us.

Steve has constructed a science problem space and phrases such as “project we were given” indicate that a lack of flexibility with regard to that problem space. That statement in particular is troubling because it is the designers’ job to define that problem space. Whether he recognizes it or not, they have, in fact, created a problem space, but one that is framed as a science rather than engineering problem.

Finally, the team begins to speculate about possible modifications to the sensor, but these ideas still lack a design orientation as they do not emerge from customer needs. Ideas are brought forward in an ideation like manner, yet not to solve a problem identified by customer needs; rather, they attempt to make their project appear to be design:

Dillon: So, we're gonna have to modify it to place it inside. Is that gonna be enough for a technical analysis 'cause we're gonna have to figure out how to re-encase it and see if it's like the proper fit for the device.

Michelle: Um, well, when you showed me the transcutaneous sensor it seemed like you were just gonna take out the, uh, temperature-

Dillon: No, 'cause-

Michelle: -and I thought that that was all the modification. [This was certainly all that was mentioned in their presentation]

Dillon: Oh no, oh no, well, we don't have sensor yet so we can't tell you exactly what we're gonna do to it. [They do have *detailed* patent drawings of the device so they should be able to do more than speculate at this point].

Michelle: Right.

Dillon: But, we have an idea because what comes in contact with the skin is metal plate and the rest of its housed in a certain plastic. That plastic might not necessarily be compatible with the body. The metal will probably be okay, then we'll have to figure out a way re-encase it in something else and then make sure there's no, like, seams for any fluids to get into areas it shouldn't. I mean, and we're probably gonna have to try a few times and that's why we have like 10, 20 rats. 20? We have 20 rats?

Steve: Yeah.

Michelle: So basically you'd have to try to make a casing for it that would?

Dillon: Yeah and that's probably where we're gonna have to analyze it.

Steve: And then not to mention that we're gonna have the confirmation of how that thing is designed, it's designed to go on the earlobe, right, so like, it clips, like we're gonna have to change it so that everything is not on the interior so it sits. Does that make sense?

Bob: So all that, we're not, like, so we're not, like the circuitry or the algorithms for it but we are gonna have to take it and, and how can we change it and, and probably make a few prototypes until we get one that's efficient and not too far from like…

Bob's last suggestion incorporates the idea of iteration, however, even as they propose possible redesign options, they continue to struggle to make their project seem like design. Steve brings the focus back to the novelty of their project's science goals, at least in terms of the course. This novelty that excites Steve troubles Michelle and Dr.

Davies because it is effectively a substitution for a design project. As Steve expresses this, Daniela once again turns to Michelle and expresses a dissenting point of view:

Steve: I mean, say, I mean like a surgical procedure, I mean, that's not considered any sort of technical, like, a surgical procedure and, like, taking readings in a rat's stomach, I mean, something that nobody else has even ventured to do in this course.
Daniela: Well, we're not designing anything.
Steve: Yeah, I know. […]
Daniela: I don't know, it'd be neat to build it.
Bob: You just want to build something.
Daniela: Yeah, yeah. [laughter]
Bob: Modifying is enough.

Bob's statement that "modifying is enough" is a compromise but would afford a real design perspective. However, we will see that there is no reason to modify the sensors once they have them in hand.

Because of concerns about how this project is progressing, Dr. Davies has agreed to meet with the team (Feb. 19th). All team members are present and take notes. He knows that the team has become defensive with Michelle and begins by telling them that she has been conveying his concerns, then emphasizes that this course is very different from their past coursework, because it is "a lot less structured" as they "step off into real world," and that it is a "Loosey-goosey environment" in which "the job is figuring out what you're supposed to be doing and then, um, you go ahead and do it and you continue figuring out what you're supposed to be doing while you're doing it for quite a distance until you're really able to focus." This statement encapsulates his expert characterization of design as iterative problem solving in which the problem and solution co-evolve (Dorst & Cross, 2001). He further explains that some projects:

> -start out looking purple and they end up looking pink. I mean, some of them really go through dramatic transformation. […] I want to see there be

a good representative engineering design. Now, in BME, we have to be careful a little bit. It's really easy to get off and to, uh, do life sciences kind of things that are not engineering, and nearly any project can, uh, have identified some appropriate engineering dimensions for it and, uh, I think this is an important part of your education experience. […] I encounter this in my own research and can identify all sorts of neat medical things to work on. The question is, '*What can you really uniquely contribute as an engineer?'* Somebody across the street, this brilliant life scientist, is not gonna be able to put on the table?

The team describes their project and recent thoughts about modifications to the sensor, and Steve couches their thoughts as trying to get an "orientation of possible engineering design" but is worried because "that could possibly be more electrical engineering than biomedical." As Dr. Davies probes them on their sensor, it becomes clear that they have not considered whether the sensor might be too large to be used on a rat, and he further cautions them that the sensor is planar but the stomach is not, and that they need to consider how this will impact their device functionality. Additionally, he warns that the scale of the device to the rat may mean that the device will use up what is being measured: "Any time you measure a system, you change it. Okay- Heisenberg principle. And so, uh so your electrode sensor may work better than the other sensor or you may have a linear surface you can put it on I don't know, but these are issues you need to work out, and I think working these kinds of issues out is requiring some design [laughs] one way or another." Suddenly Steve launches into a new idea:

Maybe we could model the CO_2 concentration in non-vital organs of a rat with either computer program or if we have a high r squared value a high correlation then maybe with an equation or maybe a time dependent or maybe even this would add a whole other variable to it this would um if we

> over all these rats we would have to modify our proposal um if we took out differing volumes of blood and put them into different levels of shock. […] I think that if we're able to repeatedly show this trend, then possibly modeling it, in one way or another with the input of people who know more about that kind of stuff than I, um, that might end up being you know the type of engineering analysis and something that we could give to Dr. Jackson.

Dr. Davies agrees with this idea and makes some suggestions about parameters and uses of such a model. He tells them such a model "would just be impressive to the hilt" because

> - what engineers can do is get in and describe quantitatively what's happening at the interface between the transducer type x and transducer type y and the system that you're trying to measure that explains why you're seeing the signal- whatever readout - to me that would be the most useful model and that would be a real major contribution.

At the next weekly meeting (Feb. 25th), the team explains that, on Dr. Davies' advice, they will build a math model. However, they are having trouble getting the needed sensors, and may need to change their experiment. Michelle warns them that they need to be prepared to get harsh feedback from the head sponsor, even though their contact sponsor was excited about the model. During this meeting, they ask about statistics for analyzing their experimental data, assuming they are able to get it, and I talk to them about some possible techniques.

The sociogram for this time once again depicts observed but unreported interactions as dashed lines (Figure 6.20). The course instructor has been added to the network and located next to Steve to reflect the interaction in the above transcript, though this location will evolve as interactions change. The sponsors continue to exert a top-down influence, reflected in Steve's descriptions of him ("like the wizard of Oz or Karl Rove.") and likewise in his placement on the sociogram. Michelle, the TA, has been moved further from the team to reflect their increasing frustration with her. Daniela is observed pulling away from the team, physically standing further from her teammates during meetings, and also carefully expressing dissatisfaction with the lack of a design perspective, and for these reasons, she is located further from the others. She is also located closer to Michelle, who frustrates her at times but provides a context in which Daniela seems to be more willing to give voice to her concerns about the lack of design perspective.

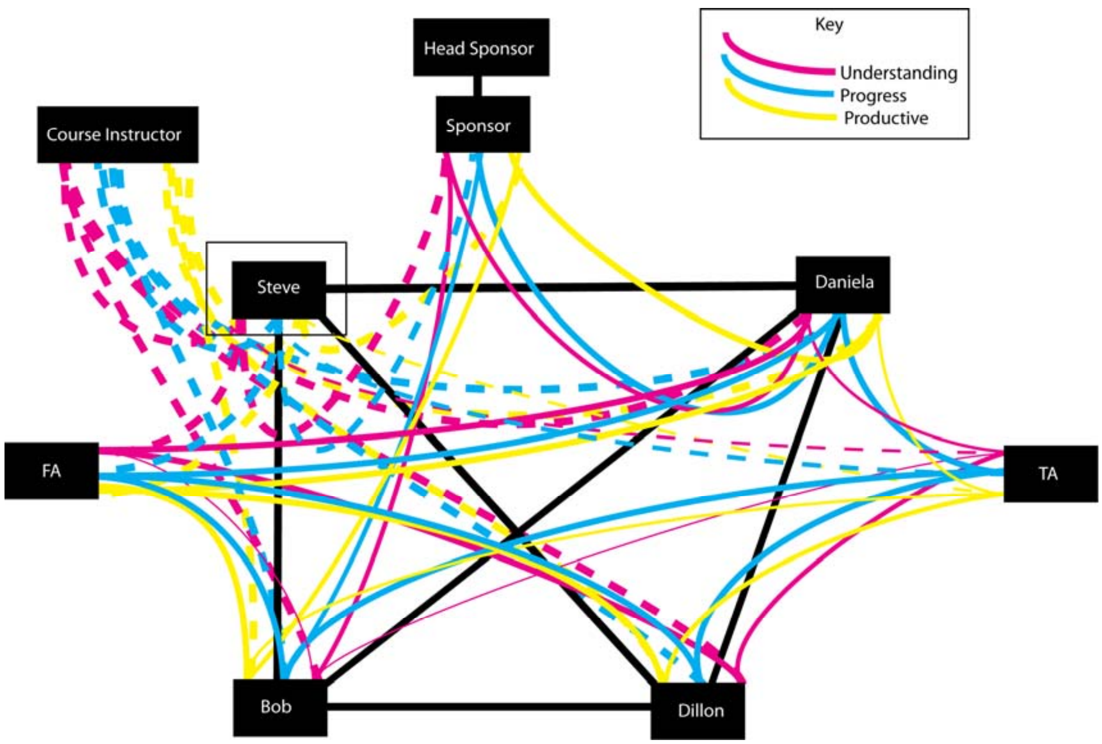

Figure 6.20 Sociogram of team 3.4 from March

One week later (March 17th), they report that they will not be able to get a second sensor, meaning that they will have to change their experiment. One sensor arrives during this week and at the March 31st meeting, they report that they have completed rat anatomy studies and determined that their one sensor will fit on the stomach without any modification needed. They still have the issue that they can only get one sensor. A further issue emerges: the animal studies are time consuming and it is difficult to get mentors to oversee them.

Dillon has begun to work on the model but is reluctant to explain it. After the TA leaves, they discuss an email from their faculty advisor who is concerned because they no longer have a hypothesis to test. The TA becomes aware of this issue the next day at the Apr 1st meeting because their faculty advisor has emailed one of the people who helps to manage the course:

Mary: His feedback to her was that he was very upset with them for not having a clear plan and following it. […] He was like 'Why are they asking now when they should have asked two weeks ago?' so he might, there might be, that might be something that you wanna know. With this sponsor, his processes and the surgeries, but they weren't really, um, following the protocol."

During the April 7th weekly meeting, the team explains that they have sent the faculty advisor and sponsor possible hypotheses and are waiting to hear back so that they may begin doing surgeries again. Michelle also asks Dillon to explain the math model, but Steve and Dillon explain that they are not ready.

The team is still putting much emphasis on experts. They have not really defined the problem and keep expecting the sponsor to do it for them, though admittedly, their challenge is that when they did, they were shot down by the head sponsor, with whom they have almost no contact.

During the meeting with the course professor the next day (April 8^{th}), Michelle once again brings up concerns about this team, and explains that she advised them to meet with Dr. Davies again because of issues they are having with their sponsor, but this is not why they have decided to meet with Dr. Davies.

Michelle: They're having some kind of weird issues with their sponsor. I guess that their sponsor, it's either their sponsor is asking them to do more work right now, um, with their animal studies or they still have both conflicting ideas about what the project they're working on. I told them they should probably talk to you since that will probably come up during the presentation and would be awkward.

Vanessa: And I think their main goal, why they wanted to talk to you, is to talk about their model so-

Michelle: Oh! [laughs]

Vanessa: Whatever went on, the thing that kind of stayed with them was talking to you about that model, so you may want to bring up how are things going with their sponsor at that meeting 'cause I think they've lost sight of that. […]

Dr. Davies: What they told me was they wanted to talk about the model. […][

Vanessa: She asked them, can you explain in English what it means and they were like "No." [all laugh] And they need to be able to do that. […] They need to know what their model does. So, I think they're hoping to kind of come to you and say um, 'What's missing from our model,' or 'What should we take out?' but, um, they need to be able to do what she asked them to do: explain it [laughs] in English not just in math.

Dr. Davies: I believe it was on that team that I made some additional comments on the report. They, they presented a model which was just a list of equations, and okay, 'So, here's the model. We satisfied the requirement for having a model.' [laughs] So my question was 'What are you gonna do with the model? Are you gonna run it, uh, interpret your experimental data? Are you going to run it to try and get a better understanding of the phenomenon that you're dealing with? And what's the use of the model other than just satisfying the need for having a list of equations that are important?'

Michelle's concerns center on the team-mentor interactions regarding hypotheses. This theme connects to the privileging of science over design, because the Sponsor takes a design approach to the animal studies rather than an experimental approach, changing the hypotheses once he is satisfied about the initial feasibility. The FA sees the team changing their hypotheses and refuses to help them with surgeries until they commit to a specific hypothesis. Michelle and I explain this to Dr. Davies:

Michelle: I guess I should say specifically that one of the team members spoke to the sponsor about the progress and the results that they've obtained from the animal study this far- just two -and so he has said he wanted to confirm with the sponsor that our hypothesis is, um, that you see a some kind of linear trend, um, with CO_2 levels during shock because, I guess, during some of their surgeries the team would, um, tell Dr. Roberts that they wanted to look at certain things because their sponsor wanted to see something and I guess Dr. Roberts was like, I'm not gonna do anymore animal studies until you figure out what you're supposed to do. […] The sponsor decided somewhere along the line maybe they want to look at something else so I, I really don't know, like, what's going on anymore.

Vanessa: Well, I saw an email from the sponsor that was like, you know, since 10 rats should really be plenty for one thing, so the next rats after that you should try other things.

At the April 20th meeting, they report that they have met with Dr. Davies to discuss their model, and feel they were on the wrong track and are now "back to the beginning" according to Bob. Dr. Davies brought up the idea of modeling it with an electrical circuit but this has the team a little confused and they are not sure why they would do this ("doesn't make much sense to me" says Steve) or even if they are "supposed to" do this, as Daniela puts it. When Michelle suggests they seek out another expert to help with their model, they discuss two experts they could ask, their faculty advisor or another BME faculty member, Dr. Marr. They settle on Dr. Marr because as Steve explains "I'd rather Dr. Marr, Dr. Roberts just…he knows too much, he knows too much! You get in there and try to talk to him about things like this and it's too much. Seriously I mean, Dr. Marr might be a better choice."

Steve is frustrated because "there's too many people giving us input on this thing and there's too many people that are telling us different things." Michelle asks if they have heard back from their sponsor and Steve explains his frustration over this:

Steve: Oh yeah, he got back to us with two solid written hypotheses and changed 'em even from the conversation we had two days prior but it's simply monitoring on the stomach CO_2 during shock and your increase is gonna be directly proportional to blood volume taken. […] I don't know, that really got frustrating- the hypothesis after he, cause I told him the situation. I was like, look, I need you to just, generally outline them. I mean it's like he changed the hypothesis after seeing the results and it's like, it's not, like we showed our initial hypothesis- you could monitor CO_2 during shock, linear, blah, blah, blah- and he was like, discusses for an hour with me and then tweaked the hypothesis again, which like, in my opinion, screws everything up because you're changing, you're changing what the experimental model was.

Michelle: So did you talk to Dr. Davies about that at all? ‘Cause I mentioned at our faculty meeting that you're having some conflicts with your sponsor about what your hypothesis is.

Steve: I mean, I wouldn’t use the word conflict. I would say difference of opinion is probably the best, because he keeps wanting to alter and modify and it's like, that’s not how things, if, with [the overseeing agency] and we have other people waiting, working with you.

During the April 21st meeting, they report that two of the team members, Steve and Daniela, can now perform the surgeries with supervision. When Michelle asks about their model, Dillon says that it is "almost finished," and that he is closer to being able to "present it in English," but is reluctant to explain further.

The sociogram for this time again includes dashed lines to represent observed but unreported interactions (Figure 6.21). At this point, the course instructor, who has continued to mentor the team, is now located closer to Bob and Dillon, who work on creating the mathematical model originally posed by Steve. Additionally, the members of the animal testing facility (represented as a one unit because Steve tends to discuss them as an entity rather than as individuals, and from his perspective, one person is very much interchangeable with another in terms of overseeing their tests) are placed near Steve. Though Daniela also has contact with them, she rarely mentions them. Michelle is now moved even further from the team, representing their continued frustration with her. She expresses her awareness of this to me, but is unsure how to remedy it. Daniela is still located further from the others, again representing her physical stance when interacting and her reliance on Michelle to give voice to her concerns about their project.

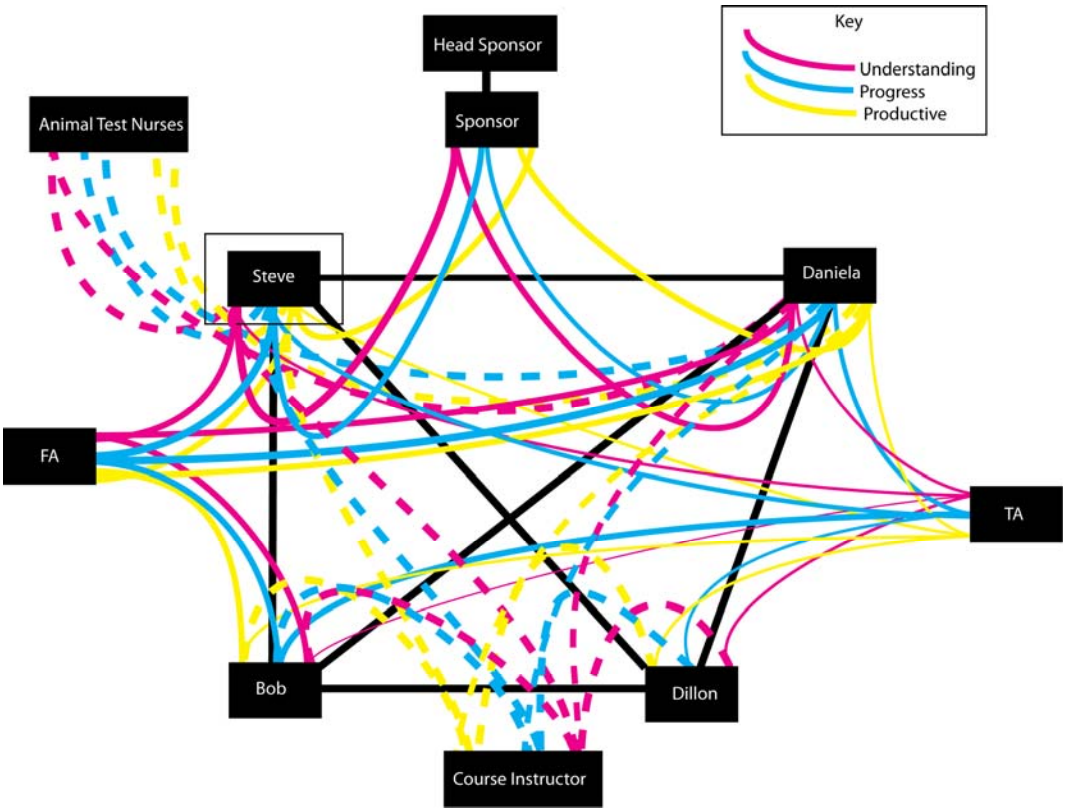

Figure 6.21. Sociogram of team 3.4 from late April

At their final presentation, attended not only by the Dr. Jackson, the head sponsor and a nurse but also Steve's mother, girlfriend, and two of the women who helped observe the surgeries, they are able to present the model "in English." They explain that they did not have to modify the sensor at all because it had a built-in temperature control and turned out to be biocompatible.

The sponsor is very impressed with their work and encourages them to write it up in a journal. He feels they have met their goals because they have demonstrated that this is feasible and worth exploring further.

At the end of the semester, one of the members comments in a survey that "There was no design portion to the sponsored project. The design portion was assigned by Dr. Davies halfway through the project." Furthermore, this aspect was "created to fulfill graduation requirements." When responding to a question about what helped them, three members mention team work and other mentors.

On their early design work, they were rated by experts as having a score of four out of five on Efficiency and a three out of five on Innovation; for their final design, they were rated as a five on Efficiency and a four on Innovation. The team's Cohesion initially mimics the overall trends observed in the class, but at the end of the course their scores diverge, particularly with regard to Understanding and Progress.

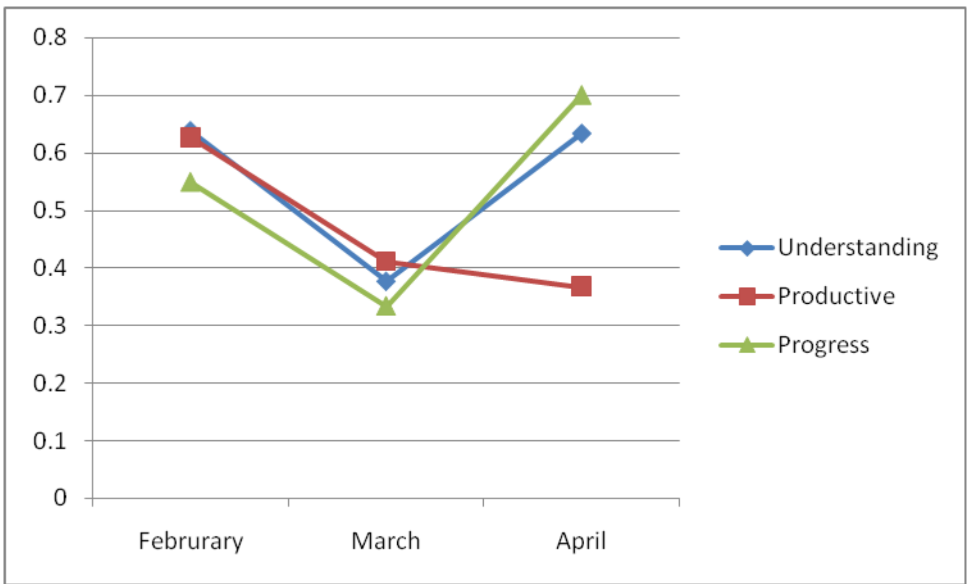

Figure 6.22. Cohesion over time for Team 3.4

Cross Case Analysis

The narratives of these three case study teams negotiating impasses in design process highlight some commonalities and idiosyncrasies. Though they all face design impasses, they function in very different ways and have very different experiences. Some of this may be attributed to differences in the particularities of their projects, sponsors, faculty advisors, and other mentors. Certainly some projects, such as the devices of Teams 3.2

and 3.3, lend themselves to being framed as a design problem rather than as a science problem.

By comparing their timelines and focusing on common experiences across teams, it is readily apparent that the impasses are made public to the whole team and TA approximately three months into the project (Figure 6.23). Team 3.2 spends time a larger amount of time iterating on their initial solution before rejecting it, whereas team 3.3 and 3.4 propose and reject initial solutions relatively quickly. Team 3.4 spends much of their time in this fashion, cycling through possible solutions and rejecting them as they struggle to adopt an engineering design perspective. Perhaps because team 3.3 begins with a device in hand, their solutions more quickly become practical, and because they settle on a workable design solution earlier, they have more time to iterate their final design than the other teams. This may explain in part why their final design was rated by experts as more innovative than the others. Had the other teams had time to iterate on their final design, they may have also produced more innovative solutions.

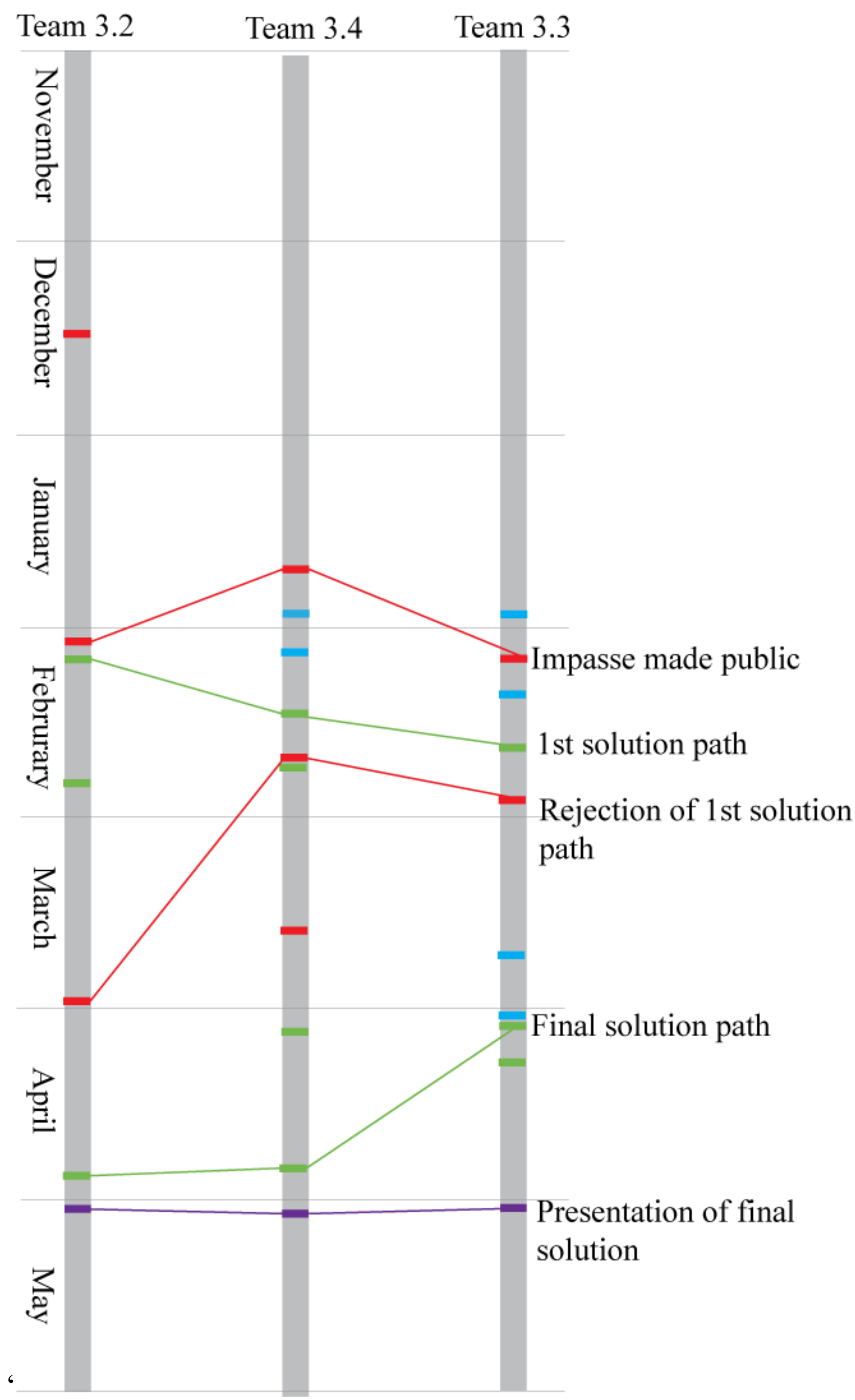

Figure 6.23. Timelines of case study teams

The teams change over time, in terms of the roles the students take on, in terms of how tasks are divided, and in terms of their perception of their mentors. There is greater diversity across teams, however, rather than across time (Figure 6.24). This diversity is hidden by statistical models, but by evolving hybrid qualitative/quantitative sociograms as an interpretation of the teams, the diversity becomes more apparent while remaining tied to the quantitative models.

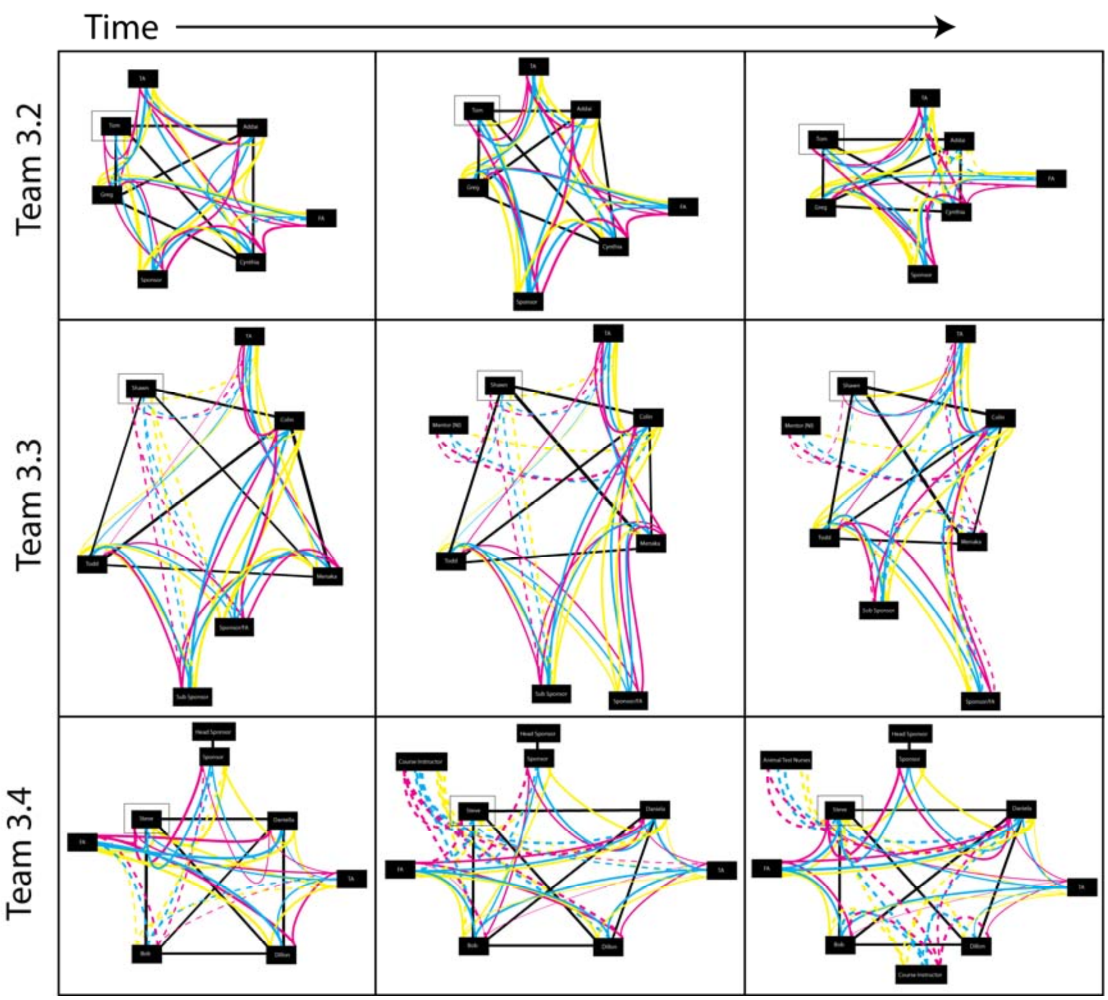

Figure 6.24. Hybrid sociograms across teams and over time.

Origins of an Impasse: Science and Theoretical Perspectives versus Engineering Design Perspectives

All of the case study teams faced impasses with origins related to adoption of science or theoretical perspectives. Team 3.2 explored the theoretical space of their design problem such that they delayed prototyping. Once they framed their problem as a design problem, they were able to provide a design solution, which did not solve their original theoretical problem, because in practice, it was not a relevant problem. Team 3.3's impasse emerged as a result of theoretical but not practical understanding of their project. They lacked the experience to judge how hard trouble shooting their device would be. Team 3.4's impasse was driven by science perspectives as well. Though the project lent itself to being cast as a science problem, they were expected to make a design problem out of it. It is not surprising that this was a challenge for the students given the coursework in their background and the capstone design model.

The difficulty of applying engineering science perspectives in design is acknowledged (Dunn-Rankin, et al., 1998) but not explained, in terms of why it occurs. The students in the case study teams lack design experience and therefore cannot rely on such experiences as they proceed in design. Because they have completed significant engineering science and science course work, they rely instead on these experiences to understand how to frame their design projects. Design projects must be defined by the designers. This aspect stands in stark contrast to the types of engineering science problems they are used to solving. Negotiating these impasses is an opportunity for significant learning both about design process and about the scientific content related to their design problems.

Negotiating an Impasse

Whereas the teams were more similar than different in terms of the origins of their impasses, how they negotiate them is quite diverse (Table 6.1). Though all case study teams distributed tasks during this process, there were a number of differences across teams in terms of how these subtasks were negotiated. In teams 3.2 and 3.4, the tasks were negotiated such that they understood how their tasks interrelated. This was less commonly true for team 3.3, in which Shawn would assign tasks and explain how they ought to be done; as a result, his team mates did not really seem to understand the impasse.

Though they all used resources to some extent, there are differences in how they located and used the resources. Team 3.2 sought out no outside mentors and did not much rely upon their faculty advisor, but did incorporate expertise from various research sources. In team 3.3, Shawn in particular sought help from experts and was adept at applying it. He was also willing to question expert suggestions, and this was not generally the case for team 3.4. Though they sought out many mentors, they needed support in incorporating (and critiquing) mentor expertise into their understanding.

There were also differences in who became involved in the design impasse in a meaningful way. Though all the team mates may feel the pressure of a lurking impasse, not all seem to have the power to negotiate the impasse, particularly if they do not understand the impasse. Part of coming to understand the problem space may be understood from the concept of storytelling, as described in an ethnographic analysis of in-situ professional design practice (Lloyd, 2000).

Storytelling may establish the experience of a problem in such a way to make it easily referenced. Storytelling may also stand in for actual experience (Schön, 1983). Explaining the impasse in a story that serves as an index to the problem provides the team members with an exemplar for understanding the impasse and a short hand for referencing it. This is most obvious in Team 3.2, with Tom’s special case. Whereas Tom uses this story to invite his teammates into the problem space to jointly negotiate their impasse, in team 3.3, Shawn shields his team mates from the problem space and effectively forms a secondary design team, even when Colin occasionally attempts entre. To understand the success of this team, in terms of Innovation scores by experts, it is therefore critical to consider the various experts who helped Shawn negotiate the impasse. In team 3.4, the entire team is at once in the problem space of the impasse, simply because it is accessible to all of them from the beginning.

In addition to inviting his team mates into the problem space, Tom maintains the joint problem space by being receptive to new as well as previously rejected ideas. This is not observed in the other case study teams, in which ideas are immediately exposed to criticism. For instance, when Colin attempts to explore the problem with Shawn, or when Daniela encourages her team to adopt a design perspective. Receptivity supports the formation of an apprenticeship model within the team. Though this occurs somewhat within Team 3.4, in which Daniela and Steve teach the others about the animal surgeries they conduct, it occurs to a lesser extent as compared to Team 3.2. Tom carefully let his teammates construct their understanding of the impasse, providing situations for them to probe their nascent understanding. Though this was time consuming, the result was that all team members understood why the impasse was problematic and when reframed and resolved through a design solution, all team members understood why the phenomenon, which in theory had been so problematic, was in practice so transient.

Table 6.1. Strategies employed by case study teams. Dark green indicates the strategy was observed on frequently, pale green indicates the strategy was observed occasionally, and white indicates the strategy was observed seldom

Team	**Distribution of tasks**	**Negotiation of tasks**	**Incorporation of Expertise**	**Help-seeking**	**Receptive to ideas**	**Apprenticeship**
3.2						
3.3						
3.4						

A similarity across the case study teams is an aspect of how they resolved their impasses. In all cases, they make significant headway once they begin to “mess about” with the actual prototyping process. Because they lack the background experiences expert designers possess, they cannot accurately predict what aspects will be particularly challenging within their design projects until they begin prototyping. For Team 3.2, in particular, they do not really define their design problem until they begin prototyping. Prior to prototyping, their project is a theoretical science project.

Next I triangulate the findings from the case studies with the statistical models from Chapter Five.

CHAPTER SEVEN: TRIANGULATION AND CONCLUSIONS

Triangulation

> … a thousand circlets spread,
> And each mis-shape the other. Stay awhile,
> Poor youth! Who scarcely dar'st lift up thine eyes-
> The stream will soon renew its smoothness, soon
> The visions will return! And lo! He stays,
> And soon the fragments dim of lovely forms
> Come trembling back, unite, and now once more
> The pool becomes a mirror. (Coleridge, 1895)

Triangulation of my findings occurred much as Coleridge described: flowers cast into water interrupt it, scatter it into pieces that then reunite into a singular phenomenon. This process was greatly facilitated by my use of hybrid sociograms, allowing me to begin triangulation as I was analyzing the case studies, moving between differing aspects of the same phenomenon.

I produced team level regression models predicting Final Efficiency and Final Innovation. I explained higher Final Efficiency as a function of higher Team Feasibility, higher Early Innovation, higher early Cohesion and higher late Cohesion. Using this model with my case study teams, team 3.3 is accurately predicted to have the lowest Final Efficiency, however, team 3.4 is predicted inaccurately to have the highest Final Innovation (Table 7.1, Figure 7. 1). This model does not produce a perfect fit, as it is an approximation of class-wide trends; thus such minor aberrations from the trend are not necessarily cause for concern.

Table 7.1. Predicted and Observed Final Outcomes for Case Study Teams

Team	Predicted		Observed	
	Final Efficiency	Final Innovation	Final Efficiency	Final Innovation
3.2	4.4	3.3	5	4
3.3	4.1	4.4	4	5
3.4	4.7	4.6	5	4

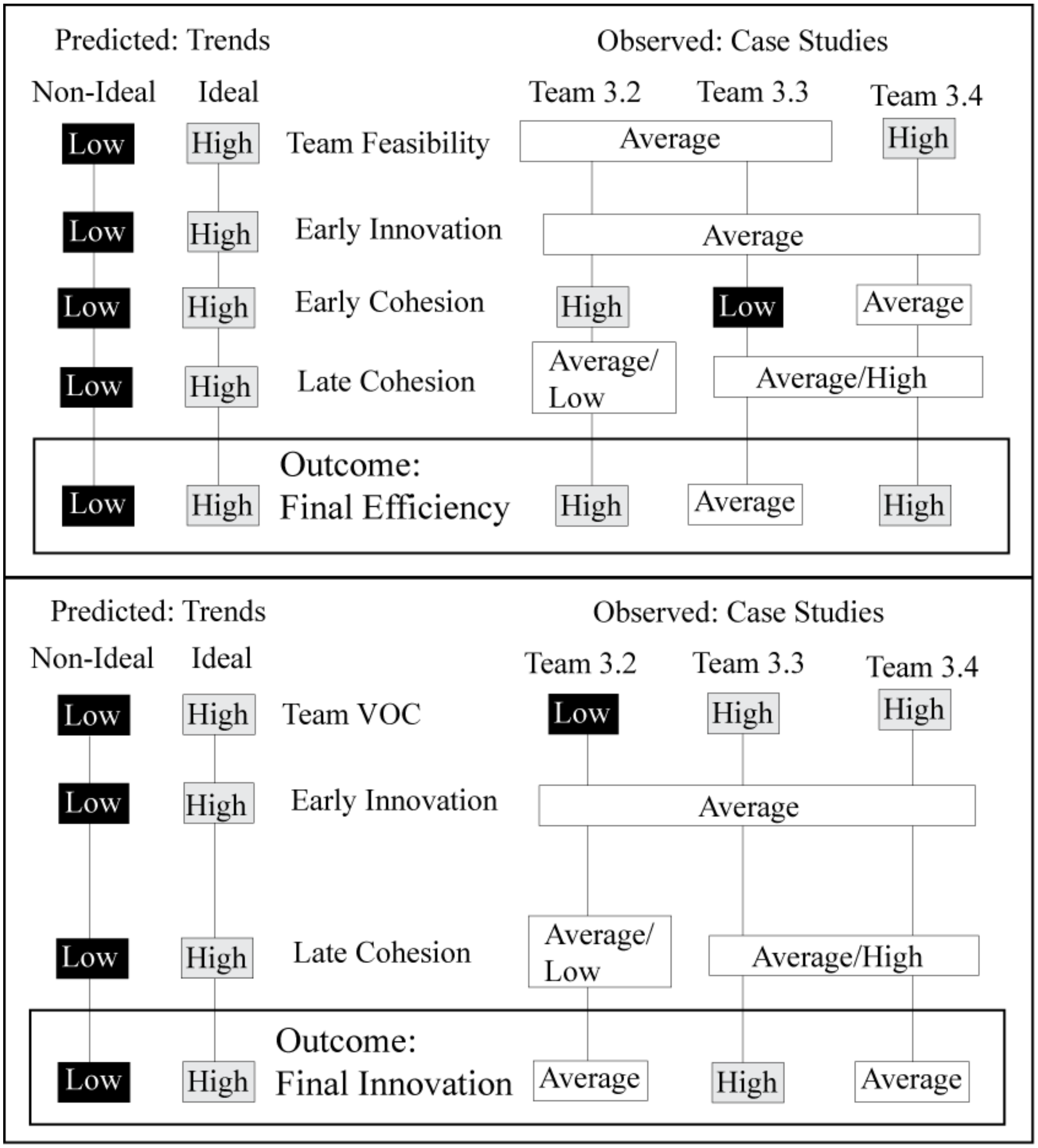

Figure 7.1. Triangulation of case study teams with the statistical models of Final Innovation and Final Efficiency

What should be, but rarely is, called into question by researchers is the assumption of a close relationship between process and product. In this case, this means assuming that innovative products indicate something about innovative process. As the process of interest in this case is not design, per se, but rather *learning* to design, this assumption should be critically examined. Triangulation of my findings provided an opportunity for this.

Though the statistical models are meant to reflect trends about innovative and efficient outcomes, the underlying *motivation* is to approximate how to support student learning of design process and how to place students on trajectories towards being innovative designers. In the case study teams, students were observed employing various strategies which may be considered to have an Efficiency focus and/or an Innovation focus. Classification of these strategies must be with regard to the process of *learning to design* rather than design process itself. An appropriate strategy for professional designers may be to hire a new team member who brings specific expertise, rather than spending time to learn about it themselves. In the context of students learning to design, the same cannot be said; although they have completed extensive coursework to prepare them for their design projects, they commonly remark that they learn content specific to their problems.

I therefore assume that learning further content and skills should be considered as an integral piece of their design learning, and consider the relative Innovativeness of observed strategies for learning (Figure 7.2). Incorporation of expertise from resources has an Efficiency focus because it is least likely to lead to further questions, whereas seeking help from outside experts can be considered to be both, because though the goal may be to gain needed conceptual understanding, allowing an expert into the problem space tends to open the space to unexpected directions, inviting in other perspectives, problems, and possibilities. The expert may make unexpected suggestions or reveal problems the students had been, as yet, unaware. This is pithily expressed by Steve, when he describes their decision to seek help from one mentor over another: “I'd rather Dr. Marr, Dr. Roberts just…he knows too much, he knows too much! You get in there and try to talk to him about things like this and it's too much.”

Opening the problem space to all members of the team through apprenticeship further expands the problem space. Though bringing in others to help may seem an efficient way to solve a problem, in the context of design problems, which must be defined by the designers, bringing in others actually increases the complexity of the problem space. However, it also increases the potential for finding an innovative solution, though this cannot be a foregone conclusion because this is tied to other strategies. Such apprenticeship may not be appropriate in the professional design studio, particularly given relatively stable practice, in this context this was a very effective strategy for learning both content and design process.

Teams were observed engaging in various actions to support their negotiation of ill-structured problems (Figure 7.2). The most basic of these is to distribute tasks within the ill-structured problem across individuals. This was observed across case study teams and also reported at their final presentations by many teams as their modus operandi. Some teams also spent time negotiating their tasks such that they had some understanding of what they were doing and choose what they were doing. This is in contrast to team 3.3, in which the team leader dealt out tasks to individuals. A team that distributes but does not negotiate tasks may look like Searle's Chinese room (Searle, 1980): as a system, they may produce a design or speak Chinese, but they lack understanding. Finally, receptivity to ideas and multiple perspective taking allow the students to understand how what they are doing impacts what their teammates are doing, and also facilitate an apprenticeship model by allowing participants to voice unpopular perspectives. Perspective taking also keeps the design tied to the needs of the customers.

These strategies also produce a range of expected levels of Cohesion, which here is defined by variance in perceptions of each other and of mentors. Strategies that bring the team together, through negotiation of tasks, by being receptive to one another's contributions, or by teaching one another would tend to offer more opportunities for students' perceptions to converge. This was the case in team 3.2, the team most frequently observed engaging in apprenticeship and being receptive. Likewise, for the teams that were not observed engaging in such strategies (teams 3.3 and 3.4), their perspectives took longer to converge and therefore their early Cohesion was lower.

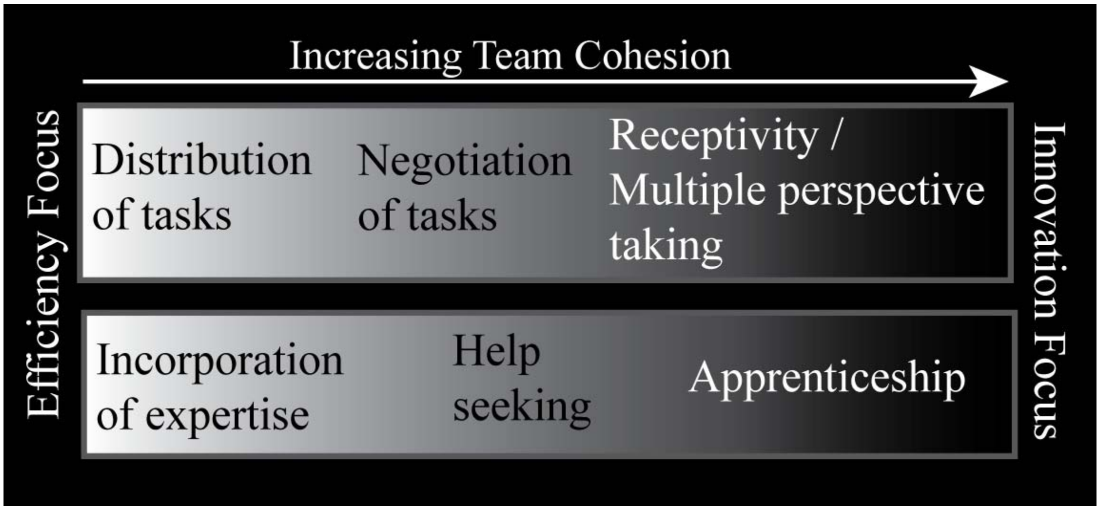

Figure 7.2. Observed design learning strategies arrayed by focus

This organization of strategies in a spectrum from Efficiency to Innovation is only relevant when taking a team-level perspective. Likewise, this array would look different if it reflected a relatively stable professional design team's practice. Rather, this models the fundamentally social process of learning design process. This model is based upon the case studies and social network analysis. How might it reconcile with the statistical models presented in Chapter Five?

The model of Final Innovation includes Voice of the Customer, Early Innovation, and late Cohesion. The model of Final Efficiency includes Feasibility, Early Innovation, early and late Cohesion. Team 3.2 and 3.3 have higher observed than predicted values for Final Innovation whereas team 3.4 had lower observed than predicted values for Final Innovation. This misfit is greater than for Final Efficiency with the case study teams. While this is expected given the relative fit of the two models, triangulation with the case study data provides the opportunity to consider what might be missing in the current model of Final Innovation. Though I cannot conclude with certainty the specific aspects, given that there are a number of strategies described, I can narrow the range to those that seem likeliest as a next step.

Given that scores for team 3.2 and 3.3 are underestimated and that scores for team 3.4 are overestimated, I begin by considering which strategies team 3.4 was not generally observed engaging in. This includes incorporating expertise and being receptive to ideas. Another difference is that team 3.3 had sufficient time to iterate on their final design solution (Figure 6.23), whereas the other teams did not. Both teams 3.2 and 3.3 were more adept at incorporating expertise; perhaps a measure of this would explain some of the variance in Final Innovation. Another possibility is that a combination of these could better account for the scores. For instance, receptivity and opportunities to iterate on the final solution path could produce a better fit. These could be operationalized in a number of ways, for instance, as an approximation of opportunity to iterate, time spent engaged with the final solution path. Receptivity could be operationalized as peer evaluation, or generated from team conversations. If we could also include further measures related to process, something technology may be able to provide, we would be able to create better statistical models. I next consider these issues framed by research on collaboration and reflective practice.

Discussion

Collaboration

To further understand learning process during collaboration, it is useful to consider dimensions of collaboration. Mercier and colleagues (2008) defined four emergent dimensions: ‘teamness,’ open communication, creation of a joint problem space and commitment to learning. They explain that while “it is possible to create an acceptable product without attention to these dimensions, it is less likely that students will learn optimally from the process without them” (Mercier, Goldman, & Booker, 2006, p. 467). This comment highlights the challenge presented by using only measures of products rather than of processes. By incorporating a measure of interaction (e.g., Cohesion) I was able to better approximate the learning process. Cohesion, I argue, is reflected in the dimension of teamness, but what is missing in terms of these dimensions, and perhaps could be more easily operationalized, is commitment to learning.

These dimensions provide a useful lens for considering differences across the case study teams and for considering the statistical model. Teamness involves feelings of belonging to a group with a common goal (Mercier, et al., 2008). This is somewhat reflected in the idea of Cohesion, which is essentially a measure of how similar team members' perceptions of themselves and their mentors are. Having high Cohesion means having agreement within the team, which may be achieved through the same types of behaviors that would tend to provoke teamness. Furthermore, Cohesion tends to increase over the course of the semester as the student ratings of their mentors decline, also suggesting something about the development of teamness. Cohesion may not encompass teamness entirely, however, because Cohesion does not imply anything directly about how positive or negative the team experiences are, merely that they perceive them similarly. If a team has uniformly negative perceptions about their efforts, can they be said to have teamness? While Cohesion seems related to teamness, it may be a slightly different dimension.

Open communication means communicating about goals and expectations of the projects as well as about timelines, constraints and misunderstandings throughout the project (Mercier, et al., 2008). This relates to the receptivity of teams to new ideas, to reconsidering old ideas, and to how students negotiate the design. Such communication supports the development of joint problem space, in which the team collectively defines the design problem. In order for this to occur, they may need a commitment to learning because it is unlikely that all members will be equally prepared to occupy the same joint problem space.

Team 3.2, which had the highest early Cohesion, also exhibited teamness, open communication, worked to establish and maintain joint problem space, and had a commitment to learning, which was evidenced by their apprenticeship model. Commitment to learning was a missing aspect within team 3.3, in which Shawn sought outside mentors to help him negotiate the impasse. Team 3.3 lacked a strong sense of teamness, reflected both by their low early Cohesion and by their interactions. For instance, Shawn delegates tasks, but does not allow them to be negotiated by his team mates, such that they do not have a common goal, rather they have their perceptions of Shawn's goals.

Commitment to learning may intersect with the degree to which students view the project as relevant and authentic. Though the authenticity of these design projects (they are actually hired to design and there is clear potential for patents to arise out of many of the projects) should prevent a missing perspective problem (O'Connor, Godfrey, & Moses, 1998), this is not the case with team 3.4. For instance, when Daniela asked about how the sensor would be used, whether it would be left in the patient, Steve asks her if she means "like are you talking about in real life?" By contrast, in team 3.2, Addai talks about his possible solutions being "real world relativistic."

Though the missing perspective is essentially tied to a missing design perspective, it is made more salient when team 3.4 is coerced into applying a design perspective via authority rather than need. They lack a sense of what a "significant and solvable" design problem is (O'Connor, et al., 1998). Their practice does not have much in common with what Schön describes as reflection-in-action (1983), discussed next.

Towards Reflective Practice

Characterizations of reflection-in-action have sometimes been conflated with the concept of self reflection (Stempfle & Badke-Schaub, 2002) and therefore assumed to be potentially threatening by, in team settings, exposing an admission of weakness or uncertainty. For instance, "We do not agree with Schön, however, in that individuals and teams do self-reflection *by themselves*. In the teams we have observed so far, we have not yet met a single 'reflective practitioner'" (p.493). Though the process Schön describes operates in relative uncertainty, it is not the designer but rather the problem space that holds the greatest uncertainty. Reflection-in-action is framed as a conversation with the situation that allows the designer to mentally test possible design decisions ("moves") prior to settling on a solution pathway in an ill-structured problem.

For the expert designer, there is feedback in the situation; the materials "continually talking back to him, causing him to apprehend unanticipated problems and potentials" (Schön, 1983, p. 101). Even when there is uncertainty in the situation, the designer may continue this process of move testing, maintaining "fidelity to the "musts" by which the freely chosen "what ifs?" are to be judged" (p.101) while considering multiple possible directions. This "playful activity" involves shaping the situation into something more desirable (Schön, 1983). In the virtual/mental world, constraints are reduced, enabling a more playful space, though the virtual/mental world is only useful if it reliably represents the actual world (Schön, 1983).

Instead of using the virtual/mental design space for generative purposes, the teams see the limitations. Because they lack the repertoires of more expert designers, they cannot effectively use the virtual space to design until they have begun prototyping; they cannot locate the design problem because they lack design experience. Because they tend to delay prototyping, they have little hope of iterating on their final solution path. For experts, the virtual/mental world serves as a sort of proving ground because they may transfer in sufficient understanding, relying on past experiences to see the current unique situation *as* already present in their repertoires; for novices, this is less feasible. For an expert designer, problem scoping may be populated with numerous design thought experiments, termed "moves" by Schon, but for these students, who draw upon their past engineering science coursework, the problem scoping space is populated by scientific and theoretical thought experiments (Schön, 1983).

There is a disconnect between the problem scoping and the prototyping in that the actual prototypes exist in an engineering design space whereas much of the problem scoping was conducted in engineering science space. Though from a very different context, research on young children drawing their planned designs before prototyping has relevance; when asked to draw prior to using the materials their drawings had little connection to the actual designs enacted, but when allowed to play with the materials prior to prototyping, their drawings did reflect their designs (Anning, 1994). Likewise, prototyping makes the engineering design perspective salient to the students, and allows them to begin making designerly decisions.

Conclusions

Through this study, I sought to add to our understanding of how students learn to design in the context of biomedical engineering. By triangulating data and findings from different aspects of an in-situ engineering design course, I have explored design as a context for learning a complex social process while creating products that may or may not be judged as innovative. As a review, the specific questions I sought to answer were as follows:

- How can I quantify interaction within design teams and their mentors?
- What is the relationship between how Innovative and Efficient team designs are judged to be by experts and measures of design skills, perceptions of learning opportunities, perceptions of mentors and team mates, and team cohesion?
- How might I characterize novice design problem scoping and the transition towards being solution focused?
- How might students in teams interact and leverage resources and mentors and as they learn to design products, and how does this reflect, contradict, or extend statistical models of whole class trends?

I therefore draw the following conclusions to those questions:

- Social network analysis provided a way to quantify interaction. Using social network analysis, I generated a team level measure of cohesion from student reported ratings of interactions within the team and with mentors, and provided corroborating evidence from other individual measures (Student Negotiation and Voice of the Customer as perspective taking) that this measure reflected the ideas of cohesion. This analysis proved challenging due to missing data, resulting in scores occupying a different range than those without missing data; I designed a practical correction factor which brought these scores back into the same space.
- Across Cohorts, there is no direct relationship between Early Efficiency and Final Innovation, and furthermore, although students' scores increase on measures of design skills, these alone do not account for variance on Final Innovation or Final Efficiency. However, by also including team Cohesion, I accounted for much of the variance in these outcomes. Variance in Final Efficiency may be accounted for as a function of Early Innovation, early and late Cohesion, and team Feasibility, with all relationships positive. Variance in Final Innovation may be accounted for as a function of Early Innovation, late Cohesion, and team Voice of the Customer, with all relationships positive.
- Within the case studies, I found that the teams engaged in extended problem scoping framed as science or theoretical activity, and that only when they began prototyping (generally with less than a month left), did they define their problem as a design problem. They relied on their experiences in prior engineering science classes to guide them, but these were inadequate for designing. Because this occurred late in the semester for two teams, they did not have sufficient time to iterate on their final design solution paths.
- The case study teams negotiated their design impasses using a number of strategies. Though they all distributed tasks and relied on mentor expertise,

they differently sought out others for help. In one case, the team leader invited his team mates into the problem space, whereas in another, the team leader sought outside expertise, shielding his team mates from the problem. The case studies reflect the trend described by the statistical model, but also highlight other aspects important to Innovation of their designs, such as opportunities to iterate on final solution paths.

Implications and Future Directions

These findings have implications for the context in which the study took place and for similar contexts, for triangulation of mixed methods research, and to a lesser extent, for other less similar contexts. Linked to some of these implications are further questions for study.

For those implications or recommendations based on the statistical models, it is important to remember that correlation is not causation. The relationships may be spurious or may all be outcomes of some other as yet undetected cause. Furthermore, generalizability is limited by using in-situ data which are not a random sample of the population. Implications must therefore be considered somewhat tentative. Likewise, implications and recommendations based primarily on findings from the case studies must also be considered as tentative in their transferability, but should still be considered as potential avenues for further research. By pairing these methods and triangulating my data and findings, some of these concerns are lessened.

Related to University Level Engineering Design

The finding that Early Efficiency consistently does not correlate to Final Innovation is important because it runs counter to traditional practice, in which students are asked to master conceptual knowledge prior to applying it towards solving novel problems. This finding would suggest that this practice should be questioned. Though this research was conducted in specific settings and is not directly generalizable, it does raise questions for other contexts.

The general trends for the class show that Cohesion increases over the course of the semester as the scores for the mentors decrease over the semester, with the sponsor rated highest and the teaching assistant rated lowest. As the students develop teamness and come to rely on each other, they rely less upon their mentors. Given that Cohesion relates to Final Innovation and Final Efficiency, it may be wise to help support teams in becoming cohesive.

Furthermore, the initial scores on the design skills test are not predictive of any final scores, meaning that regardless of initial performance, students have similar opportunities to learn to design. Taken with the model relating Early Innovation to both Final Innovation and Final Efficiency, these findings suggest that students should have access to extended team design experiences earlier in their programs. Incorporating findings from the pilot study, in which the redesign task afforded greater learning as compared to the more sequestered design task, tends to suggest that these early design experiences need not be industry sponsored projects in order to be valuable learning experiences; rather, they need to reflect key aspects of authentic design activity, such as letting the design emerge from customer needs, and encouraging the students to prototype early and to iterate upon their prototype to improve it.

Ideally, students should have earlier opportunities to engage in engineering design activities. They learn new skills and content as they design, making 1^{st} year design activities a productive endeavor. Such earlier experience would allow them to have a greater set of relevant designerly experiences to rely upon when they enter the workforce. Through earlier and more frequent design experience, students could learn to rely upon design perspectives rather than upon engineering science perspectives, even if only the senior course involves an industry sponsored project.

Findings from the case studies complement, contrast, and extend these findings. Though the case study teams were diverse, the teams were consistent in spending a large percentage of their time in problem scoping. Though this has been reported as characteristic of novice design, its attribution has been speculative. Across the case study teams, the problem scoping occurred framed as theory or engineering science rather than as practice and engineering design. Once students become solution focused as they engage in prototyping, they also become oriented towards engineering design. Within the case studies, for all but one team this was driven by the approach of deadlines. This observation may explain why the case study team rated highest on Final Innovation of product was not observed engaging in the strategies that seem to lead to the most learning and was not cohesive early in their design process. This case study team settled on their final design solution pathway earlier than the other case study teams, and had time to iterate on it, improving it.

This research has already had implications for the setting in which the research was conducted. Changes have been made to the course, reflected in the decision to continue to use the redesign task over the more sequestered stethoscope design task. Decisions about how and when to request feedback have also been influenced; the fall course instructor for 2008 altered when and how to give feedback. Furthermore, he also asked his teaching assistants to address the issues presented on peer evaluation forms, rather than simply using them to determine grading patterns.

Further changes could be made, however. Based on the finding that Early Innovation is important for the development of both Final Efficiency and Final Innovation, opportunities to practice innovation should occur earlier.

Given the finding that students perceive their sponsors as changing their understanding when they are in teams that are more Cohesive and that are rated as having lower Early Efficiency and higher Early Innovation, I would further recommend that importance of Early Innovation over Early Efficiency. Since students tend to rate their sponsors as their most important mentor, such findings tend to suggest the potential impact a sponsor might have on a team. For this reason, I would suggest the need for further research on interactions with mentors in these authentic design situations. Based on the observational findings that problems may result for teams in which few students attended meetings with sponsors, as in the case of the pilot team 2.1, I would encourage requiring that all teammates attend early meetings with the sponsor, (perhaps with one student assigned the role of primary contact).

I would recommend that students begin prototyping their device at the beginning of the second semester if this is at all feasible within financial constraints. This could engender movement towards design perspectives rather than lingering on science and theoretical perspectives, and could enable the students to more quickly define their problems as design problems. Early prototyping would allow for opportunities for further iteration, which would help not only to convey the discipline of engineering design, but also potentially allow students to move towards more innovative designs. Such early prototyping may not seem feasible, but from my observations, much of what the students end up doing with regard to their prototypes occurs over very short time periods; thus, it may be possible provided the standards are not too high initially. Earlier prototyping and related iteration require further research into impacts both on student learning of design process and on the Innovation and Efficiency of student design products.

Further research is needed to understand how to create productive relationships with mentors. Guidelines for the mentors to structure their roles would be helpful. From this research, one suggested guideline would be the following: If the project sponsor is not the same person as the contact sponsor, the two individuals should have a clear understanding of the project such that the contact sponsor can properly direct the team, Furthermore, since it is not possible to have TAs be expert in all projects, the role of the TA as a guide, not an expert should be made clear to the teams.

Further work is also needed to determine if these findings generalize to other settings and contexts. In particular, the finding that in this case, Early Innovation and late Cohesion are important for both Final Efficiency and Final Innovation could be extended by conducting similar research in a variety of design settings, both in engineering and beyond.

Equity and Identity

Delimited from this study was research explicitly considering identity and equity. This was in part because of the context; given the capstone setting, many of the students lost to engineering have already been lost well before this class. However, observations from the case studies highlighted interesting interactions between native and non-native English speakers, and between men and women in teams that lie beyond the aims of this study, but do raise questions. For instance, though the women in the case studies do not report feeling peripheral, some do report feeling they have little to contribute, even though their team mates do not report them as contributing less. How could these apparently contributing members be made to see their contributions as valid and valued?

Extensions to K-12 Settings

While my findings have already had impact on the course I research, and offer implications and avenues for further study into relating process to product and into how generalizable my findings are, how is this research relevant for K-12 settings? This question has relevance as there is a new focus to bring engineering into K-12 settings.

Rather than mimicking the engineering science coursework followed by the engineering design capstone model commonly observed in university settings, I would advise schools adopt engineering design models (Petrosino, et al., 2008; Svihla, Marshall, & Petrosino, 2008). Engineering design better reflects the discipline of engineering, and may be a better entre point for students. Past research has suggested that using design as a vehicle for science can be problematic because of differing goals (Schauble, Klopfer, & Raghavan, 1991). I extend this understanding by considering where the goals come from and considering the role of iteration (Table 7.2). In science, goals come from the community of practice, whereas in engineering design, goals come from customers. Iteration in science serves understanding, either through demonstrating reputability of results or through extending observations to further settings. In engineering design, iteration serves to improve the design, but not necessarily to improve understanding, though this may occur as a byproduct.

Table 7.2. Critical differences between science and engineering

	Engineering	**Science**
Goals from	Customers	Scientists
Role of Iteration	To Improve	To Understand

There is an opportunity in the observed extended problem scoping. I observed students incorporating more and deeper understanding of theoretical aspects of their design before prototyping. While this may be ingrained in these students, this format yet presents an opportunity for teaching science though design. By spending greater time predicting and discussing possible outcomes of a design, it might be possible to connect to theoretical or more abstract aspects of the science. However, if recursive iteration is possible, then this may yet be a more feasible route for student learning, particularly if the goals are slightly altered across iterations.

Methodological Tools for Representation and Triangulation

Social network analysis is a promising tool for exploring collaborative learning activity, such as design. When learning is assumed to be fundamentally social and interactional, including a measure of interaction is particularly productive. The incorporation of a measure of team interaction, using social network analysis, was critical to accounting for variance in Final Innovation and Efficiency. Including weighted networks rather than binomial networks was particularly useful for this. The correction factor I devised was used for practical reasons. Because I have not employed it with a random sample and contrasted it with the uncorrected versions, it requires further study. It is not specific to this context, but should be validated.

Social network analysis is also a useful complement to qualitative research. By including the various mentors on the graphs, we are afforded the opportunity to see the actual operating team, not just the team as constructed by the course setting. The mentors hold consequential roles, sometimes providing tremendous help, as in Team 3.3, and sometimes standing in the way of progress, as in Team 3.4.

My research has implications for methodological triangulation. By incorporating social network analysis with both the statistical modeling and the case study research, I was facilitated in moving between data sets. By evolving the sociograms to become interpretations of the case studies, I had to consider how the data sets related to one another. By using social network analysis to produce a measure of interaction, I was able to explain more about a fundamentally social and interactive process: learning to design.

APPENDIX A: DESIGN TOOLS FOR DESIGNING A DISSERTATION

In engineering design, functional models describe the functions that are accomplished by the device, though not how the functions are accomplished, and depict the flow of energy, materials, and information. The device or parts of the device are represented by black boxes. In the case of my dissertation, I decided to focus on subsets of information flows, as energy and materials flows are somewhat less relevant (Figure A.1). The information flows highlighted are as follows: Understanding of Design, Theories of Learning, and Methodological Knowledge. Some of the flows are changes in personal understanding, but some outputs will contribute to the community of practice understanding.

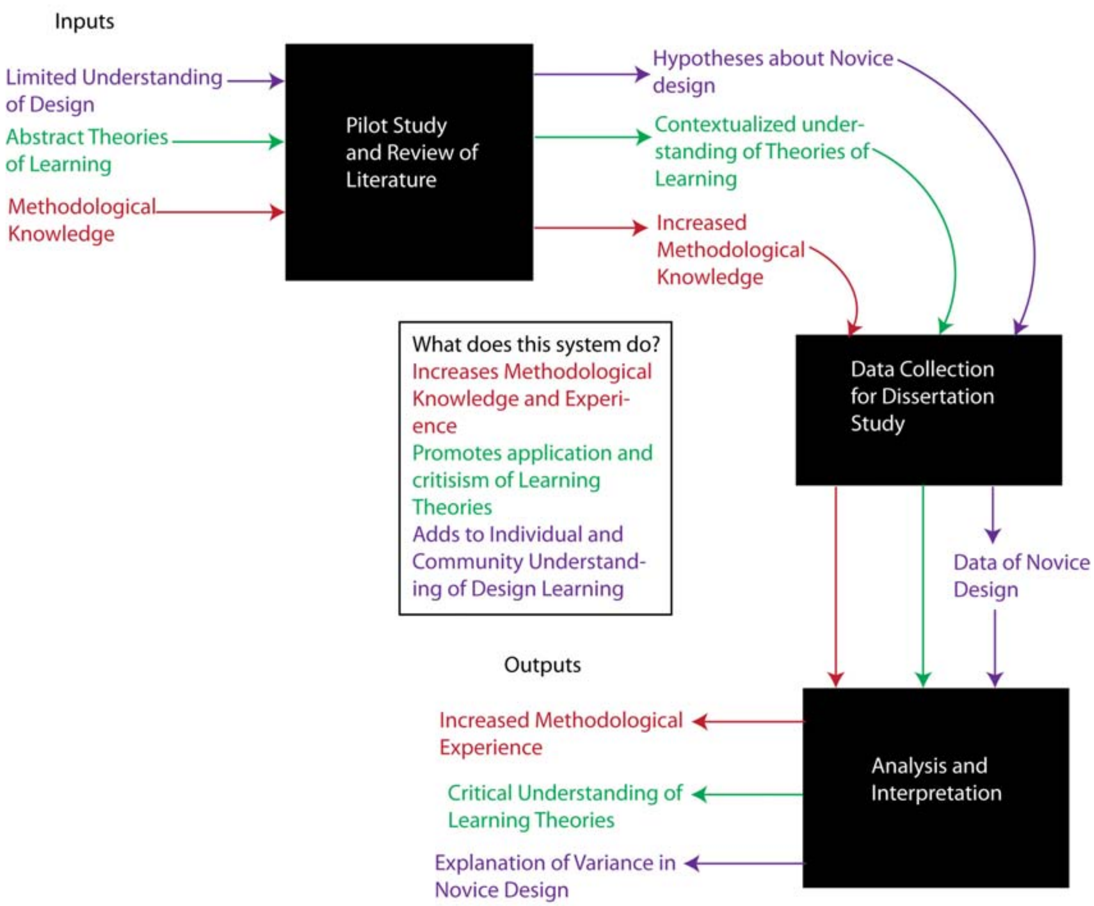

Figure A.1. Functional model depicting flows of information through the dissertation study

My dissertation (or any dissertation) may be considered as an example of design process. As such, tools used by the population I study (and used by many practicing engineers) are also employed throughout (Figures A.1 and A.2). The dissertation has many functions for various customers. My role as designer of this study was to determine who my customers were and what their needs were, keeping in mind that tradeoffs needed to be negotiated (for instance, a many-year longitudinal study would be useful for examining the long term impact of the course, but in order to satisfy the customer need of a "timely" graduation, this option is not considered viable). Customer needs were translated into functions in order to incorporate them into the study design. This process helped establish the significance of the study design.

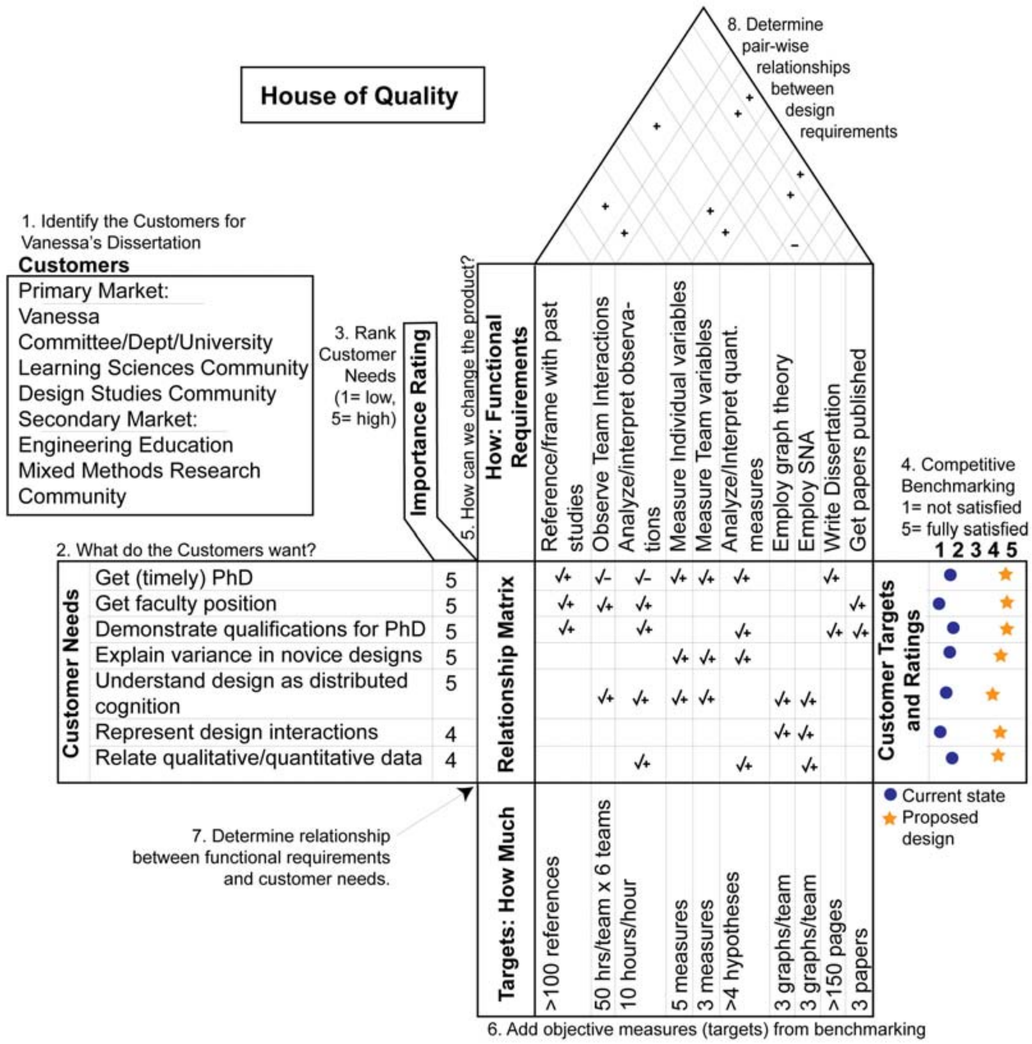

Figure A.2. Representation of Quality Function Deployment as a House of Quality

APPENDIX B: PROJECT LIST

Key:	
ECE	Electrical and Computer Engineering
BME	Biomedical Engineering
ME	Mechanical Engineering
KHE	Kinesiology and Health Education
CS	Computer Sciences

Cohort 1		
Project	Sponsor	Advisor Field
Proposed Design of an Enhanced Vision System for Surgical Applications	Hospital	BME
Device for the Removal of Carbon Dioxide from Exhaled Breath Condensate	Industry	BME
An Injectable Polymer Scaffold with Mesenchymal Stem Cells as a Repair Device for Annulus Fibrosus	Industry	BME
Hemodialysis Laboratory Module Design	University	BME
The Virtual Brace: A Device for Treating and also Preventing Back and Neck Pain	University	BME
Mars Advanced Radiation Acquisition (MARA) 1: Remote Imaging System (RISA)	Government	BME
Design of Metal Nanoparticle Conjugates for Live Cell Molecular Interaction Imaging	University	BME

Medical Equipment Repair, Calibration, and Distribution Facility in Honduras for Central American Medical	Industry	BME
Mars Advanced Radiation Acquisition (MARA) 2: Instrumentation Temperature Sensing Circuit (ITSC)	Government	ECE
Design of an Adaptive Postural Stability Acoustic Feedback System	University	ECE
Endotracheal Intubation Stylet Camera	Hospital	BME
Stem Cell Isolation System	Hospital	ECE
Design and Testing of a Non-Invasive Intracranial Temperature (NIICT) Monitor and Phantom	Industry	BME
A Novel Concept for the Diagnosis of Heparin-Induced Thrombocytopenia	Hospital	BME
Endoscopic Surgical Device Proposal	Hospital	ME
ANS Tunneling Device	Industry	BME
Advanced Infant Temperature Feedback Thermal Environment Control for Portable Incubators	Industry	BME
Cable Connection Device for Spinal Cord Stimulation	Industry	BME
Arthroscopic Mapping of Articular Cartilage	University	BME
Design of a Product Simulation Based on Modulation of the Baroreceptor Reflex Circuit	Industry	BME
Computer-Based Instruction of Using	Universi	BME

Periodontal Probe	ty	
Moisture Vapor Transfer (MVT)	Industry	BME
Cohort 2		
Project	Sponsor	Advisor Field
Feedback System to Optimize Delivery of Vagus Nerve Stimulation Therapy	Industry	BME
Atraumatic Laparoscopic Grasper	Industry	ME
Skin Interface Physiology Network	Industry	BME
Design of a Prototype Manufacturing Capability for a Nitinol Orthopaedic Implant	Industry	ME
Gene Vectors for Diagnosis of Hyper-Proliferative Diseases in the Oral Cavity	Industry	BME
Non-Invasive Ileus Reversal Device	Industry	BME
Bioresorbable Foam that Maintains Air Premeabilty During Degredation	Industry	BME
Mechanical Testing of Cardiac Catheters	Industry	BME
Enhanced Vision System	Hospital	ECE
Real-time Calorimetric Measurement od Hematocrit	University	BME
Design and Evaluation of Arthroscopic Delivery Tools of Injectable Hydrogels	Industry	BME
Synthetic Plantar Fat Pad Prosthetic	Industry	KHE
Artifical Airways: Development of a New Edotracheal Tube	University	BME
Prosthetic Leg for Central American Amputees	Industry	ME

Precordial Lead System that allows for ease of use, Proper Electrode Placement, and Diagnostic Quality ECG Signal Acquisition	Industry	ME
Hybrid Robotic Gripper	Industry	ME
Osteovation Bone Void Filler Mixer/Delivery System	Industry	BME
Remote Imaging System Acquisition: Telemedicine Imaging Instrumentation	Govern ment	BME
Physical Thermal Model for Premature Infant	Industry	BME
Sensor for Detecting and Recording Mechanical Vibrations Induced by Radio Frequency Pulses Absorbed in Biological Material	Govern ment	BME
Bio-Sample Information Network with Daedalus Software	Industry	CS
Laryngopharyngeal Acid Reflux-Induced Cough Exhaled Breath Condensate Collection Process	Industry	BME
Flow Phantom to Simulate Blood Flow in Cerebral Aneurysms for Use with a Clinical Magnetic Resosnance Scanner	Hospital	BME
Cohort 3		
Project	Sponsor	Advis or Field
SCRAP Sample Concentration	Industry	BME
GloFish® Embryo Sorter	Industry	BME
Design of Improved Measurement of Spasticity	Hospital	BME

Development of a Drug-Delivery Catheter	Industry	BME
Lumbar Fusion Methods for Spinal Surgery	Industry	ME
Pore Density Non-Conformity Mapping System	Industry	BME
Sensor for Recording and Measuring Mechanical Vibrations Induced by Radio Frequency Pulses Absorbed in Biological Material	Govern ment	BME
Evaluating and Optimizing an Arthroscopic Delivery Tool for Injectable Hydrogel to Repair Cartilage Defects and Treat Joint Diseases	Industry	BME
Enhanced Vision System (EVS)	Hospital	BME
Design and Implementation of a Circulatory System Flow Bench	Industry	BME
Integration of an Ultrasound Transducer into a Tissue Optical Clearing Device	Industry	BME
Closure of Incision Wounds Through Abdominal Adipose Tissue	Industry	BME
Design and Prototype of Seahorse Veridoser™ Device	Industry	BME
Developing a LabView-based Control System for an Instron Materials Testing Device	Universi ty	BME
Material Options for Peristal™ for the Prevention and Treatment of Hemorrhoids	Industry	BME
Continuous Monitoring of Airway Acidity on an Ambulatory, Mobile Patient	Industry	BME
Midfoot External Fixator System	Industry	ME
Remote Imaging System Acquisition (RISA):	Govern	BME

Space Environment Multispectral Imager	ment	
Prosthetic Ankle for Central American Amputees	Industry	KHE
Sensor Options to Detect Gastric Mucosal Carbon Dioxide In Situ	Industry	BME
In Vivo Adipose Tissue Surrogate	Hospital	BME
Design of Translumenal Procedures for Determining Safe Locations for Gut Lumen Exit During Surgery	Hospital	BME

APPENDIX C: PRE, MID, AND POST DESIGN SKILLS TEST

Instructions
This test will not be graded, but points will be given for completion of the problems.

Please allow 15 minutes.
Do not go over the allotted time, even if your answers are incomplete. We are interested in how you begin to work on these problems, and you will not be expected to finish them.
Do not use outside resources. You may use a calculator, but do not use the internet, notes, textbooks, or any other sources of information.

Do not spend more than 15 minutes on this problem. Do not use outside resources or consult with anyone else as you are working on this problem. If you write on any other paper while answering this problem, please attach it to this test.
This is a very complex problem. A full solution would require extended attention and a number of iterations. However, one of the keys to success in extended problem solving is how you get started. Our goal is to access how you get started on a problem.
Your task in this problem is to begin designing the device described below.

In severe trauma patients hypothermia is a common occurrence and issues in a significant increase in mortality. This situation is particularly grave for wounded soldiers for which it has been shown that mortality doubles when the body core temperature reaches a value of 34°C or lower. Patients suffering from severe trauma tend to become hypothermic regardless of the environmental temperature, and in a war zone, such as the recent US involvement in Iraq and Afghanistan, casualties have suffered hypothermia at a rate in excess of ninety percent. Consequently, the prevention and treatment of hypothermia have been identified as being a major deficiency in American combat medical capability.
The Department of Defense is seeking solutions to solving the problem of preventing and treating hypothermia in war casualties. Owing to constraints imposed by the battlefield environment, there are a number of very specific limitations that must be enforced for any possible solution. Rapid evacuation to a Forward Surgical Hospital typically requires five hours and a ride in a cold helicopter. To be effective a warming device must be able to transmit energy to the body core at a rate of 60 watts over the five hour period. It has been determined that the most effective method of delivering heat directly to the body core is via arteriovenous rewarming, being far more efficient than any surface warming technology. The device must be compact, light in weight, and

robust (capable of being dropped from a helicopter at 150 feet onto a concrete surface.) The device must contain its own power supply since there is generally not an external electrical service available on a battlefield and during critical phases of transport. Batteries are too heavy and are inefficient. Thus, the energy source of choice for heating is compressed butane which can be used to fire a burner in a small heat exchanger through which a minor fraction of the patient's blood flows. A surgical group has proposed designing a unit capable of warming 300 ml of blood per minute. The pumping source to move blood through the heat exchanger is the patient's own heart. Access to the patient's arteriovenous system for this device will be the same as standard practice for a heart lung machine.

The proposed device holds tremendous potential for providing life-saving support for trauma patients in both the military and civilian populations. At the present time it is still in the concept and prototyping phase of development. Since the early studies have been accomplished via some ingenious but intuitive work by a team of surgeons, there is no basis for understanding and predicting performance based on a rational model of the device when attached to a patient.

APPENDIX D: DESIGN SURVEY

This measure was given to Cohort 3 in November, and a similar measure will be given in April (omitting redesign questions). A similar measure was given to Cohort 2 in September, November, and April.

This survey is for research and evaluation purposes and will not affect your grade. Your individual answers will not be shown to the professors or to your team mates, however, your answers will help us to make informed suggestions about revising the course. Please answer honestly and completely. Your responses will help us to improve how bioengineering design is taught. Note that Vanessa will compile the responses and provide general class responses (and a list of who completed the survey) to Dr. Tunnell, but he will NOT have access to individual responses. Your answers will remain confidential. The first part will ask about your REDESIGN project then about the SPONSORED project.

1. What device did your team REDESIGN?
2. What customer need did your redesign address?
3. Did you have any familiarity with the device you redesigned PRIOR to the redesign project? If yes, please explain.
4. When working in a group, how important is it to you that everyone agrees on a decision or a course of action? [Extremely Important, Very Important, Important, Somewhat Important, Not Important]
5. For the redesign project, did your team experience any problems related to working as a group? If yes, please explain.
6. How did you decide what aspect of your device to redesign?
7. What helped you in completing your redesign project?
8. Who did you ask for help, or ask questions of while working on your redesign project? (Please list by name)
9. For each of the following activities, rank how useful you thought it was for completing the REDESIGN project:
10. Gantt Chart[Extremely Important, Very Important, Important, Somewhat Important, Not Important]
11. Assembly Instructions[Extremely Important, Very Important, Important, Somewhat Important, Not Important]
12. Pugh Chart[Extremely Important, Very Important, Important, Somewhat Important, Not Important]
13. Voice of the Customer[Extremely Important, Very Important, Important, Somewhat Important, Not Important]

14. Functional Model [Extremely Important, Very Important, Important, Somewhat Important, Not Important]
15. Benchmarking[Extremely Important, Very Important, Important, Somewhat Important, Not Important]
16. HOQ[Extremely Important, Very Important, Important, Somewhat Important, Not Important]
17. Ideation[Extremely Important, Very Important, Important, Somewhat Important, Not Important]
18. What made your redesign project challenging?
19. Please describe your team's relationship with your TA.
20. Which of the following activities do you think will be important for your sponsored project? Check all that apply. [HOQ, Pugh Chart, Gantt Chart, Ideation, VOC, Functional Model, Literature Review]
21. What problem does your sponsored project address?
22. Who are your customers for your sponsored project?
23. What do you need to learn, that you do not already know, in order to complete your sponsored project?
24. How motivated do you feel by the sponsored project as a design problem? [Very motivated, Somewhat motivated, Not very motivated]
25. How relevant is your sponsored project, in terms of addressing a real problem? [Relevant, Somewhat Relevant, Neutral, Somewhat Irrelevant, Irrelevant]
26. How many hours per week did you spend on BME 370 on average?
27. Name three things you liked about the course
28. Name three things that could be improved in the course
29. Since beginning your sponsored project, how frequently have you met with your TA (not counting the week of Thanksgiving)?
30. Since beginning your sponsored project, approximately how frequently have you interacted as a team, not counting meetings with your TA? Please estimate how many phone calls, emails, meetings, etc per week (on average). (For example, 3 emails per week, one non-TA meeting per week, 5 text messages per week...)
31. Since beginning your sponsored project, approximately how many interactions have you had with your sponsor? Please estimate how many phone calls, emails, etc.
32. Since beginning your sponsored project, approximately how many interactions have you had with your Faculty Advisor? Please estimate how many phone calls, emails, etc.
33. Have you interacted with anyone other than your TA, Faculty Advisor, Team, and sponsor as part of your sponsored project? If yes, please name the person, describe their relationship to you (classmate, graduate student, friend, proffessor, professional engineer, etc), and briefly describe the interaction.
34. Considering the various interactions (with TA, Faculty Advisor, Sponsor, as a team, and anyone else you have met with) you have had during your sponsored project so

far, what has helped you most? (Briefly describe an interaction that was productive for the sponsored project)

35. Briefly list the steps you use to design
36. What is the difference in process between design and redesign?
37. A team of engineers need to meet a customer need in a biomedical device. The engineers have found four possible solutions, which have great potential, three of which are very cheap to implement. In fact, the three together would cost less than the fourth option. What would you advise them to do? How should they proceed?
38. What makes a design motivating, interesting, or exciting? What would make you choose one design project over another?
39. Given two design problems with the same type of content, which would you prefer? A project related to: [Preventing a disease, Curing a disease]

Thank you for your participation! Your honest responses really help us to understand how design is learned, and how to improve how it is taught.

APPENDIX E: CODING SCHEME FOR PRE, MID, AND POST DESIGN TEST

Feasibility

- Price – price of the final product, e.g., “can’t be too expensive”
- Regulations – federal and/or military regulator boards, e.g., “must meet FDA requirements”
- Materials – durability and/or biocompatibility, e.g., “use tubing that is lined with something to prevent blood clotting”

Voice of the Customer

- Patients – addresses soldiers’ potential concerns, e.g., “has to be able to be used while laying down”
- Doctors – addresses doctors’ and/or medics’ potential concerns, e.g., “display panel shows blood temp going in and out”
- Practicality – addresses the needs of the demanding setting presented in the question, e.g., “the butane must be contained effectively so it won’t explode when dropped 150 feet”

Diagram

These categories refer ONLY to what is drawn and labeled in a diagram, and ONLY what is correct, according to the original question

- Material – the blood flow, must indicate flow direction
- Heat – the heat source and method, must show container and burner
- Mechanical – what provides the pressure for the blood, must indicate it is the heart and not a pump
- System Boundaries – shows the person, the tubing, and the device, must include all three

APPENDIX F: RUBRIC FOR DOMAIN EXPERT SCORING OF DESIGN PROBLEM DEFINITIONS AND FINAL DESIGNS

To what extent is the content required by the project beyond BME coursework?	To what extent did the team effectively use content in their design?	How much potential did the project as described offer opportunities to be innovative?	How innovative was the final design?
1= not at all, 5=Completely	1= not at all, 5=Completely	1= Little Potential, 5=High Potential	1= not at all, 5=Extremely

Any other comments?

APPENDIX G: THE CONSTRUCTIVIST LEARNING ENVIRONMENT SURVEY (CLES)

The survey is a 5-point Likert scale (1=Almost Never; 2=Seldom; 3=Sometimes; 4=Often; 5=Almost Always).

Personal relevance

1. In [my previous engineering coursework/ this class] I learned about the world beyond my classroom setting.
2. In [my previous engineering coursework/ this class] my new learning started with problems about the world beyond
3. In [my previous engineering coursework/ this class] I learned how engineering can be part of my life beyond my
4. In [my previous engineering coursework/ this class] I got a better understanding of the world beyond my classroom
5. In [my previous engineering coursework/ this class] I learned interesting things about the world beyond my class
6. In [my previous engineering coursework/ this class] what I learned had nothing to do with life beyond my class

Critical voice

7. In [my previous engineering coursework/ this class] it was acceptable for me to ask "why do I have to learn this."
8. In [my previous engineering coursework/ this class] it was acceptable for me to question the way I was being taught.
9. In [my previous engineering coursework/ this class] it was acceptable for me to talk about activities that were confusing.
10. In [my previous engineering coursework/ this class] it was acceptable for me to talk about anything that prevents me from learning.
11. In [my previous engineering coursework/ this class] it was acceptable for me to express my opinion.
12. In [my previous engineering coursework/ this class] it was acceptable for me to speak up for my rights.

Shared control

13. In [my previous engineering coursework/ this class] I planned what I was going to learn.

14. In [my previous engineering coursework/ this class] I decided how well I was learning.
15. In [my previous engineering coursework/ this class] I decided which activities were best for me.
16. In [my previous engineering coursework/ this class] I decided how much time I spent on learning activities.
17. In [my previous engineering coursework/ this class] I decided which activities I did.
18. In [my previous engineering coursework/ this class] I assessed my learning.

Student negotiation

19. In [my previous engineering coursework/ this class] I had a chance to talk to other students.
20. In [my previous engineering coursework/ this class] I discussed how to solve problems with other students.
21. In [my previous engineering coursework/ this class] I explained my understandings to other students.
22. In [my previous engineering coursework/ this class] I asked other students to explain their thoughts.
23. In [my previous engineering coursework/ this class] other students asked me to explain my ideas.
24. In [my previous engineering coursework/ this class] other students explained their ideas to me.

APPENDIX H: INTERACTION SURVEY FOR SOCIAL NETWORK ANALYSIS

You are being asked to complete this survey as part of a study on how students learn to design, and as a means to evaluate and improve THIS class. Your answers will not affect your grades. Your answers will be kept confidential, but findings, which are anonymous, may be shared with the professor. Please answer honestly and independently to the best of your ability.

SECTION 1: General information

The following questions pertain to the people with whom you have recently interacted with related to your design project. Many of the questions pertain to meetings. If you did not attend a meeting, it is okay to leave the related questions blank. Very little is known about this area, and your honest answers will help us understand what leads to productive design interactions. Additionally, your information will help us recognize any problems you might be having with you team, TA, Faculty Advisor, or sponsor. Again, you answers are confidential.

SECTION 2: Meetings with your TA

1. Not counting the weekly TA meeting, how have you interacted with your TA in the last SEVEN DAYS? Check all that apply (leave blank if none apply): [TA emailed us once or twice, TA emailed us several times, I emailed the TA once or twice, I emailed the TA several times, I met with the TA one additional time, I met with the TA two additional times, I met with the TA more than two additional times, I have talked on the phone with my TA, The TA suggested I contact someone for help/resources/advice/etc, The TA introduced me to someone, in person or by email]
2. Did you attend the most recent meeting with your TA? [I was present for all or most of the meeting, I arrived late or left early, and missed at least 25% of the meeting, I missed more than half the meeting, I did not attend the meeting (SKIP TO SECTION 3)]
3. If you attended the most recent TA meeting, estimate (to the nearest 15 minutes) how long it lasted. Times are in minutes: [15, 30, 45, 60, 75, 90, >100]
4. If you attended the most recent TA meeting, was anyone absent from this meeting? If so, who?
5. If you attended the most recent TA meeting, please rate your level of agreement with the following statement. This meeting changed my understanding of our design project. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]

6. If you attended the most recent TA meeting, please rate your level of agreement with the following statement. This meeting was productive. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
7. If you attended the most recent TA meeting, please rate your level of agreement with the following statement. Significant progress was made towards our design project because of something that occurred at this meeting. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
8. If you attended the most recent TA meeting, what occurred? Check all that apply. Remember that unless otherwise specified, answers should be relevant to the design project. [I/we needed help, I/we prepared for an upcoming deadline I/we addressed administrative needs, We argued, Someone proposed a potentially useful new idea, I learned something new, We spent some time talking about something not related to the project]
9. If you attended the most recent TA meeting, did anyone contribute something significant or important during this meeting that changed your understanding or plans for the design? Please write the person's name and describe the contribution.

SECTION 3: Meetings with your Faculty Advisor

10. How have you interacted with your Faculty Advisor (FA) in the last SEVEN DAYS? Check all that apply (leave blank if none apply): [FA emailed us once or twice, FA emailed us several times, I emailed the FA once or twice, I emailed the FA several times, I met with the FA one additional time, I met with the FA two additional times, I met with the FA more than two additional times, I have talked on the phone with my FA, The FA suggested I contact someone for advice/information/etc, The FA introduced me to someone, in person or by email]
11. In general, how frequently do you meet with your Faculty Advisor? [Never, Once, Monthly, Every other week, Weekly, More than once a week]
12. Did you attend the most recent meeting with your Faculty Advisor? [I was present for all or most of the meeting, I arrived late or left early, and missed at least 25% of the meeting, I missed more than half the meeting, I did not attend (SKIP TO SECTION 4)]
13. If you attended the most recent Faculty Advisor meeting, estimate (to the nearest 15 minutes) how long it lasted. Times are in minutes. [15, 30, 45, 60, 75, 90, >100]
14. If you attended the most recent Faculty Advisor meeting, who else was present?
15. If you attended the most recent Faculty Advisor meeting, please rate your level of agreement with the following statement. This meeting changed my understanding of our design project. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
16. If you attended the most recent Faculty Advisor meeting, please rate your level of agreement with the following statement. This meeting was productive. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]

17. If you attended the most recent FA meeting, please rate your level of agreement with the following statement. Significant progress was made towards our design project because of something that occurred at this meeting. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
18. If you attended the most recent Faculty Advisor meeting, did anyone contribute something significant or important during this meeting that changed your understanding or plans for the design? Please write the person's name and describe the contribution.

SECTION 4: Meetings with your Sponsor

19. How have you interacted with your Sponsor in the last SEVEN DAYS? Check all that apply (leave blank if none apply): [Sponsor emailed us once or twice, Sponsor emailed us several times, I emailed the Sponsor once or twice, I emailed the Sponsor several times, I met with the Sponsor one additional time, I met with the Sponsor two additional times, I met with the Sponsor more than two additional times, I have talked on the phone with my Sponsor, The Sponsor suggested we contact someone for advice/information/etc, The Sponsor introduced me to someone, in person or by email]
20. How frequently do you meet with your Sponsor? [Never, Once, Monthly, Every other week, Weekly, More than once a week]
21. Did you attend the most recent meeting with your Sponsor? [I was present for all or most of the meeting, I arrived late or left early, and missed at least 25% of the meeting, I missed more than half the meeting, I did not attend (SKIP TO SECTION 5)]
22. If you attended the most recent meeting, what occurred? Check all that apply. Remember that unless otherwise specified, answers should be relevant to the design project.
23. [I/we needed help, I/we prepared for an upcoming deadline, I/we addressed administrative needs, I/we tested or experimented, I/we gathered information, I answered a question (relevant to the project) asked by someone else, We argued Someone proposed a potentially useful new idea, We spent some time talking about something not related to the project, I learned something new]
24. If you attended the most recent Sponsor meeting, estimate (to the nearest 15 minutes) how long it lasted. Times are in minutes: [15, 30, 45, 60, 75, 90, >100]
25. If you attended the most recent Sponsor meeting, please rate your level of agreement with the following statement. This meeting changed my understanding of our design project. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
26. If you attended the most recent Sponsor meeting, please rate your level of agreement with the following statement. This meeting was productive. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]

27. If you attended the most recent Sponsor meeting, please rate your level of agreement with the following statement. Significant progress was made towards our design project because of something that occurred at this meeting. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
28. If you attended the most recent Sponsor meeting, did anyone contribute something significant or important during this meeting that changed your understanding or plans for the design? Please write the person's name and describe the contribution.
29. If you attended the most recent meeting, what occurred? Check all that apply. Remember that unless otherwise specified, answers should be relevant to the design project. [I/we needed help, I/we prepared for an upcoming deadline, I/we addressed administrative needs, I/we tested or experimented, I/we gathered information, I answered a question (relevant to the project) asked by someone else, We argued Someone proposed a potentially useful new idea, We spent some time talking about something not related to the project, I learned something new]

SECTION 5: Other Team meetings

30. How did you locate the customers you interviewed for your sponsored project? Check all that apply. [Sponsor suggested someone, TA suggested someone, Faculty Advisor suggested someone, Already knew an appropriate customer, Another student suggested someone, Another professor suggested someone, Not suggested by anyone else, but we contacted someone ourselves]
31. Please briefly describe the roles (i.e. doctor, patient with diabetes, etc) of customers you interviewed for your sponsored project.
32. How have you interacted with your team in the last SEVEN DAYS? Include meetings with at least two members attending. Check all that apply: [My teammates emailed me once or twice, My teammates emailed me several times, I emailed my team once or twice, I emailed my team several times, I met with my team one time (outside of the TA meeting), I met with my team two times (outside of the TA meeting), I met with my team three or more times (outside of the TA meeting), I have talked on the phone with a teammate, I have exchanged text messages or IMs with a teammate, I have met socially with a teammate]
33. Please list, in hours, approximately how much time you spent in the past SEVEN DAYS working on the design project ON YOUR OWN?
34. Most sub-problems or tasks are completed individually or in pairs. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
35. Our project easily divides into sub-problems or tasks for us to work on individually or in pairs. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
36. When someone else completes a task, s/he reports back on it in a way that I can understand. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]

37. My teammates are more able to contribute to the design project than I am because they have more relevant expertise. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
38. Did you meet with anyone else (other than Teammates, TA, Faculty Advisor, and Sponsor) in the last SEVEN DAYS related to your design project? If yes, please briefly list the following information for each person: name; role (BME faculty, Customer, classmate, etc); purpose of meeting
39. Did you attend other team meetings in the past SEVEN DAYS(count meetings of two or more members as other team meetings)? [I was present for all or most of the meeting, I arrived late or left early, and missed at least 25% of the meeting, I missed more than half the meeting, Our team did not have any other meetings this week (SKIP TO SECTION 6), I did not attend any other team meetings this week (SKIP TO SECTION 6)]
40. If you attended other team meetings this week, what occurred? Check all that apply. Remember that unless otherwise specified, answers should be relevant to the design project. [I/we needed help, I/we prepared for an upcoming deadline, I/we addressed administrative needs, I/we tested or experimented, I/we gathered information, I answered a question (relevant to the project) asked by someone else, We argued Someone proposed a potentially useful new idea, We spent some time talking about something not related to the project, I learned something new]
41. Meeting with my team this week changed my understanding of our design project. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
42. Meeting with my team this week was productive. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
43. Significant progress was made towards our design project because of something that occurred at team meetings this week. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
44. Did anyone contribute something significant or important during this meeting that changed your understanding or plans for the design? Please write the person's name and describe the contribution.

SECTION 6: Ideal Team Interactions

45. In an ideal team, how important is it that the roles of each person are clearly defined so that you know what each person is responsible for? [Extremely Important, Very Important, Important, Somewhat Important, Not Important]
46. In an ideal team, how important is it that each member has something valuable to contribute? [Extremely Important, Very Important, Important, Somewhat Important, Not Important]
47. In an ideal team, how important is it ideas build on one another's? [Extremely Important, Very Important, Important, Somewhat Important, Not Important]

48. In an ideal team, how important is it to agree on a common vision for the project? [Extremely Important, Very Important, Important, Somewhat Important, Not Important]
49. In an ideal team, how important is it that each member puts a similar amount of effort into the project? [Extremely Important, Very Important, Important, Somewhat Important, Not Important]
50. SECTION 7: Evaluation of Interactions and course activities
51. Our Faculty Advisor has helped us find resources and introduced us to people (in person or by email) who can help us with our project. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
52. Our TA has helped us find resources and introduced us to people (in person or by email) who can help us with our project. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
53. Our Sponsor has helped us find resources and introduced us to people (in person or by email) who can help us with our project. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
54. My TA gives me good feedback [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
55. My TA has expertise relevant to our design project. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
56. My Faculty Advisor gives me good feedback [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
57. My Faculty Advisor has expertise relevant to our design project. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
58. My Sponsor gives me good feedback. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
59. I give my team mates good feedback. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
60. My team mates give me good feedback. [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
61. Please rate your own level of expertise related to your project. [High, Somewhat High, Average, Somewhat Low, Low]
62. Considering your team as a whole, please rate your team's level of expertise related to your project. [High, Somewhat High, Average, Somewhat Low, Low]
63. In your team, are the roles of each person clearly defined such that you know what each person is responsible for? [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
64. In your team, does each member have something valuable to contribute? [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
65. In your team, do ideas build on one another's? [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
66. Does your team agree on a common vision for the project?

67. In your team, does each member put a similar amount of effort into the project? [Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree]
68. What is challenging about your design project?
69. Name three things that could be improved with the design class
70. Name three things that are going well with the design class
71. Are you having any problems with your TA, FA, Sponsor, or team mates? If so, please explain.
72. Is there anything else you'd like to add? (If not, you can leave this blank).
73. Approximately how long did this survey take you to complete?

Thank you for completing this survey. Your answers are very important to us.

APPENDIX I: PEER EVALUATIONS

Confidential. Date: _____ Your Name:__ Team #:_____

TEAM CONTRIBUTION:

For each member of your team, **INCLUDING YOURSELF**, please estimate the percent each member contributed for each aspect of the design process. The total should **add up to 100**. We recognize that some tasks may have been delegated to one person, and that we may not have listed all relevant tasks; if you feel a significant contribution has been made that is not captured by this form, write it in on the blank line.

What % did all members contribute for each part:	**Team Leader's Name:**	**Name:**	**Name:**	**Name**:	
Contributed Useful Suggestions					**=100%**
Contact with Sponsor					**=100%**
Preparation of progress reports to sponsor					**=100%**
Share of Work Overall					**=100%**
Literature research					**=100%**
Prototyping, Experimentation					**=100%**
Preparation of Most Recent Written Report					**=100%**
Preparation of Oral Presentation					**=100%**
Other:					**=100%**

For **Overall Effort,** a score other than 25% for 4-person teams or 33% for 3-person teams indicates that individual merits consideration of a grade modification upward or downward. **Unequal ratings require written justification on the back of this form.**

Overall Effort:					**=100%**

TEAM COMPARISON:

For each member of your team, **INCLUDING YOURSELF**, insert a number from 1 to 5 indicating your overall impression of how each member of the team performed his/her duties.

1 = Never 2 = Almost never 3 = Sometimes 4 = Almost always 5 = Always

Attended Team Meetings				
Responded to Email or Other Messages				
Available When Needed				
Did Share of Assigned Work				
Turned in High Quality Work				

Do you believe each member of your team should receive the same grade?

[ ] YES [ ] NO **IF NO**, please explain your reasons on the back.

APPENDIX J: PRELIMINARY ANALYSIS OF CLES FACETS

For Cohort Two, prior coursework scores resulted in six factors, though a scree test (Cattell, 1966) would eliminate one of these. The remaining factors cover the CLES categories, except for Critical Voice, which is covered by two factors.

Rotated Factor Matrix for C2, Prior Scores						
	Factor					
	1	2	3	4	5	6
PR1_PR	0.032432	0.192023	0.838777	0.053384	-0.07168	0.101837
PR2_PR	0.206555	0.248475	0.420084	0.098279	0.040273	-0.06062
PR3_PR	0.069468	0.073252	0.617234	0.068881	0.243093	-0.14419
PR4_PR	0.006674	0.160848	0.81232	-0.03014	0.103088	-0.03816
PR5_PR	0.140001	0.244955	0.741551	0.078405	-0.07491	0.261931
CV1_pr	-0.01629	-0.14197	0.031078	0.079923	0.823194	-0.00963
CV2_pr	-0.1689	0.131904	0.213096	0.310721	0.6136	0.113586
CV3_pr	0.28711	-0.18522	0.089046	0.410737	0.2497	0.386353
CV4_pr	0.095491	0.17324	-0.12867	0.646123	0.207047	0.25936
CV5_pr	0.006832	0.12166	0.15958	0.930702	0.184086	-0.05373
CV6_pr	0.120855	0.112866	0.104197	0.710477	-0.04365	-0.14058
SC1_pr	0.076614	0.578186	0.220227	0.157144	-0.09757	-0.29525
SC2_pr	0.132655	0.639111	0.259776	0.045162	0.001386	0.250956
SC3_pr	0.126296	0.835897	0.239365	0.073178	0.10435	-0.09427
SC4_pr	0.195061	0.622776	0.100798	0.133681	-0.09178	0.031604
SC5_pr	-0.08257	0.737955	0.087497	0.085808	0.002036	-0.0052
SC6_pr	0.10034	0.558848	0.144044	-0.10923	-0.02239	0.450119
SN1_pr	0.685629	0.103753	-0.03332	0.086948	0.187915	0.323147
SN2_pr	0.856078	0.051357	-0.00225	0.04357	0.008681	0.177014
SN3_pr	0.906247	0.158123	0.128758	0.063759	0.048775	0.075786
SN4_pr	0.87475	0.026809	0.137044	0.063186	-0.14107	-0.06567
SN5_pr	0.864572	0.144537	0.112259	0.106042	-0.08765	-0.1317
SN6_pr	0.927376	0.047995	0.09276	0.007276	-0.12766	-0.07775
Extraction Method: Principal Axis Factoring. Rotation Method: Varimax with Kaiser Normalization.						
Rotation converged in 7 iterations.						

For Cohort 2, the design course scores resulted in 6 factors. The remaining factors cover the CLES categories, except for Critical Voice, which is covered by 2 factors in the same structure as for ratings of prior coursework, and for Shared Control, which is covered by 2 factors.

Rotated Factor Matrix for C2, Design Scores						
	Factor					
	1	2	3	4	5	6
PR1_PR	0.133944	0.822374	0.10847	0.08715	0.313666	0.11218
PR2_PR	0.134305	0.870407	0.253566	-0.02829	0.068941	0.183574
PR3_PR	0.186443	0.602055	0.285948	0.106492	0.363012	0.068133
PR4_PR	0.109576	0.742733	0.10783	0.169642	0.270176	0.154359
PR5_PR	0.30508	0.753909	0.168806	0.298543	-0.00257	0.209676
CV1_pr	0.157288	0.043114	0.122813	0.679725	0.172552	0.068382
CV2_pr	0.128043	0.217259	0.349818	0.611401	0.120556	0.127474
CV3_pr	0.005743	0.266931	0.592933	0.226737	0.158116	0.41444
CV4_pr	0.054588	0.182197	0.678596	0.433302	0.269136	0.275349
CV5_pr	-0.02156	0.260093	0.618749	0.223391	0.096506	0.110908
CV6_pr	0.155138	0.10083	0.790977	-0.10912	0.135038	-0.11236
SC1_pr	0.055867	0.151517	0.180936	0.069656	0.706404	0.124703
SC2_pr	0.131294	0.303571	0.229193	0.24088	0.752345	0.148825
SC3_pr	0.127148	0.133417	0.110168	0.083762	0.238167	0.764204
SC4_pr	0.261807	0.056336	0.148201	0.163693	0.39433	0.499847
SC5_pr	0.202811	0.304455	0.028967	0.097503	0.056849	0.725024
SC6_pr	0.291498	0.266045	0.037026	0.020033	0.579797	0.229494
SN1_pr	0.530961	0.12768	-0.03103	0.676786	-0.03341	0.08469
SN2_pr	0.575072	0.325117	-0.05175	0.50833	0.08191	0.341159
SN3_pr	0.780929	0.24168	0.145663	0.162199	0.263581	0.113386
SN4_pr	0.884224	0.169245	0.033098	0.26282	0.156208	0.113863
SN5_pr	0.943259	0.048876	0.133795	-0.00816	0.110773	0.135775
SN6_pr	0.887455	0.160009	-0.00396	0.183791	0.048784	0.121626
Extraction Method: Principal Axis Factoring. Rotation Method: Varimax with Kaiser Normalization.						
A	Rotation converged in 8 iterations.					

For Cohort 3, prior coursework scores resulted in 6 factors, though a scree test (Cattell, 1966) would eliminate two of these. The remaining factors cover the CLES categories, except for Critical Voice, which is covered by 3 factors, two of which would be eliminated in a scree test.

Rotated Factor Matrix, C3, Prior						
	Factor					
	1	2	3	4	5	6
PR1_Pr	0.111791	0.00943	0.765248	0.053047	-0.03357	-0.0059
PR2_Pr	0.067728	0.199782	0.518373	-0.02219	-0.02365	0.219517
PR3_pr	0.061965	0.21483	0.586056	0.156255	0.277784	0.024215
PR4_pr	0.051018	0.172453	0.81734	0.101849	0.115282	-0.05123
PR5_pr	0.096029	0.158481	0.663377	-0.00625	0.045474	-0.12173
CV1_pr	0.116171	0.338852	0.068932	0.461329	0.098025	0.482477
CV2_pr	0.065557	0.363249	-0.07971	0.436822	0.161758	0.172515
CV3_pr	-0.05914	-0.16794	0.065125	0.803335	0.070438	-0.04471
CV4_pr	-0.06206	0.185855	0.149203	0.723075	0.127528	0.007324
CV5_pr	0.225233	1.16E-05	0.042704	0.45098	0.494103	-0.05369
CV6_pr	0.107726	0.089813	0.181205	0.244223	0.731394	0.026399
SC1_pr	0.074094	0.686822	0.143045	-0.01221	0.08958	0.101972
SC2_pr	0.108452	0.650638	0.264789	0.050926	-0.01839	-0.01944
SC3_pr	0.112528	0.712353	0.073562	0.016651	0.047592	0.104987
SC4_pr	0.161602	0.491174	0.177491	0.022365	0.158866	-0.24029
SC5_pr	0.137476	0.85395	0.126202	0.098349	-0.04991	-0.14237
SC6_pr	-0.05948	0.598688	0.081742	0.057121	0.006994	0.129213
SN1_pr	0.574963	0.046157	0.047529	0.074153	0.197476	-0.3269
SN2_pr	0.825221	0.022441	0.095114	0.138412	-0.17492	-0.33434
SN3_pr	0.801566	0.23472	0.170535	0.004377	-0.02277	0.018732
SN4_pr	0.732456	0.17803	0.067939	-0.03932	0.405712	0.054128
SN5_pr	0.893138	0.047365	0.103714	-0.0275	-0.05091	0.228172
SN6_pr	0.836614	0.05423	0.047175	-0.083	0.23215	0.139631
Extraction Method: Principal Axis Factoring. Rotation Method: Varimax with Kaiser Normalization.						
A	Rotation converged in 6 iterations.					

For Cohort 3, design course scores resulted in 5 factors, though a scree test (Cattell, 1966) would eliminate one of these. The remaining factors cover the CLES categories, except for Shared Control; one question from this facet grouped with those from Student Negotiation.

Rotated Factor Matrix, C3, Design					
	Factor				
	1	2	3	4	5
PR1_Pr	0.221841	0.697854	0.171228	0.184011	0.087068
PR2_Pr	0.189587	0.72466	0.110452	0.05719	0.073006
PR3_pr	0.071278	0.789171	0.220738	0.274441	0.026779
PR4_pr	0.186891	0.78044	0.114932	0.033504	0.030341
PR5_pr	0.074235	0.731415	0.069029	0.369911	0.087756
CV1_pr	0.109267	0.10299	0.596429	0.448973	0.031285
CV2_pr	0.205499	0.08548	0.846977	0.139096	0.025608
CV3_pr	0.152896	0.071629	0.639338	0.284328	-0.02757
CV4_pr	0.152572	0.263015	0.747184	0.021821	0.156
CV5_pr	0.187137	0.191818	0.71946	0.167724	-0.13622
CV6_pr	0.180413	0.139753	0.287429	0.707333	-0.09797
SC1_pr	0.147895	0.25337	0.226006	0.650096	0.367276
SC2_pr	0.139453	0.200947	0.156627	0.823832	0.229071
SC3_pr	0.194947	0.171364	0.35852	0.368445	0.407837
SC4_pr	0.188946	0.181029	0.078743	0.750163	0.058153
SC5_pr	0.11109	0.347101	0.107859	0.452322	0.612991
SC6_pr	0.578522	0.155255	0.468277	-0.05485	0.19617
SN1_pr	0.726451	0.296664	0.204194	0.06953	0.243014
SN2_pr	0.822009	0.096622	0.16529	0.148722	0.056123
SN3_pr	0.833171	0.125968	0.134433	0.170547	0.223984
SN4_pr	0.700681	0.188262	0.207629	0.269297	0.042858
SN5_pr	0.746902	0.173841	0.128435	0.181427	-0.11788
SN6_pr	0.156559	-0.01643	-0.12141	0.024082	0.201265
Extraction Method: Principal Axis Factoring. Rotation Method: Varimax with Kaiser Normalization.					
A	Rotation converged in 7 iterations.				

APPENDIX K: HLM ANALYSIS OF CLES SCORES

Hierarchical Linear Unconditional Model of Personal Relevance

The parameters related to Personal Relevance may be interpreted as follows (Table K.1): On average, the Personal Relevance score for the design class was 3.831. The *t* test result suggests that this score is different from zero (t=60.607, $p < 0.05$).

Student Level Model
Personal Relevance, Design = $\beta_{0j} + r_{ij}$

Team Level Model
$\beta_{0j} = \gamma_{00} + u_{0j}$

Table K.1. Hierarchical Linear Unconditional Model for Design Class Personal Relevance

Fixed Effect	Coefficient	SE	t Ratio	p value
Intercept, γ_{00}	3.831	0.063	60.607	0.00
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.0004	43	38.858	>0.5
Student level, r_{1j}	0.518			

Hierarchical Linear Conditional Model of Personal Relevance

The parameters related to Personal Relevance may be interpreted as follows (Table K.2): On average, the Personal Relevance score for the Design class was 3.854. The *t* test result suggests that this score is different from zero (t=34.444, $p < 0.05$). There is no significant difference between Cohorts (t=-0.167, $p > 0.05$).On average, students score the Design class 0.163 points higher than their previous courses. This increase is not significantly different from zero (t = 0.704, $p > 0.05$). There is no significant difference between Cohorts (t=0.073, $p > 0.05$). The variance of individual scores for the Design Course is 0.001. The statistical test result suggests that scores on Personal Relevance do not differ significantly across teams ($X^2 = 30.656$, $p > 0.05$), but that variance remains to be explained in the relationship between the scores for prior coursework and scores for the design class ($X^2 = 45.011$, $p > 0.05$). Due to a low level two class, the variance may be biased. The intraclass correlation is 0.0018 or 0.18% of variation is due to teams. If Cohort is completely removed from the model, the increase approaches statistical significance (t=1.883, $p = 0.085$).

Student Level Model

Personal Relevance, Design = $\beta_{0j} + \beta_{1j}$*(Prior Personal Relevance) + r_{ij}

Team Level Model

$\beta_{0j} = \gamma_{00} + \gamma_{01}$*(Cohort) + u_{0j}

$\beta_{1j} = \gamma_{10} + \gamma_{11}$*(Cohort) + u_{1j}

Cohort was dummy coded (Cohort 2=0; Cohort 3=1). Prior Personal Relevance scores were team mean centered.

Table K.2. Hierarchical Linear Model of Design Class Personal Relevance

Fixed Effect	**Coefficient**	**SE**	**t Ratio**	**p value**
Mean score for design, γ_{00}	3.854	0.111	34.444	0.000
Cohort effect, γ_{01}	-0.024	0.142	-0.167	0.869
Prior, γ_{10}	0.163	0.232	0.704	0.485
Cohort on Prior, γ_{11}	0.073	0.274	0.266	0.792
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.001	34	30.656	>0.5
Prior Personal Relevance slope, u_{1j}	0.007	34	45.011	0.098
Student level, r_{ij}	0.548			

Hierarchical Linear Unconditional Model of Critical Voice

The parameters related to Critical Voice may be interpreted as follows (Table K.3): On average, the Critical Voice score for the design class was 3.632. The *t* test result suggests that this score is different from zero (t=50.949, $p < 0.05$).

Student Level Model

Critical Voice, Design = $\beta_{0j} + r_{1j}$

Team Level Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

Table K.3. Hierarchical Linear Unconditional Model for Design Class Critical Voice

Fixed Effect	Coefficient	SE	t Ratio	p value
Intercept, γ_{00}	3.632	0.071	50.949	0.00
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.038	43	51.433	0.177
Student level, r_{1j}	0.539			

Hierarchical Linear Conditional Model of Critical Voice

The parameters related to Critical Voice may be interpreted as follows (Table K.4): On average, the Critical Voice score for the Design class was 3.791. The *t* test result suggests that this score is different from zero (t=34.319, $p < 0.05$). There is no significant difference between Cohorts (t=-1.582, $p > 0.05$).On average, students score the Design class 0.015 points higher than their previous courses. This increase is not significantly different from zero ($t = 0.055$, $p > 0.05$). There is not a significant difference between Cohorts (t=0.310, $p > 0.05$).

The variance of individual scores for the Design Course is 0.026. The statistical test result suggests that scores on Critical Voice do not differ significantly across teams ($X^2 = 39.069$, $p > 0.05$) and that the relationship between scores for Prior Coursework and for the Design Course do not vary significantly ($X^2 = 47.328$, $p > 0.05$). Due to a low level two class, the variance may be biased. The intraclass correlation is 0.0525 or 5.25% of variation is due to teams.

Student Level Model

Critical Voice, Design = $\beta_{0j} + \beta_{1j}$*(Prior Critical Voice) + r_{ij}

Team Level Model

$\beta_{0j} = \gamma_{00} + \gamma_{01}$*(Cohort) + u_{0j}

$\beta_{1j} = \gamma_{10} + \gamma_{11}$*(Cohort) + u_{1j}

Cohort was dummy coded (Cohort 2=0; Cohort 3=1). Prior Critical Voice scores were team mean centered.

Fixed Effect	Coefficient	SE	*t* Ratio	p value
Intercept, γ_{00}	3.791	0.110	34.319	0.000
Cohort, γ_{01}	-0.223	0.141	-1.582	0.121
Prior, γ_{10}	0.015	0.337	0.055	0.957
Cohort on Prior, γ_{11}	0.310	0.347	0.921	0.363
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.026	34	39.069	0.252
Prior Critical Voice slope, u_{1j}	0.273	34	47.328	0.064
Student level, r_{ij}	0.489			

Hierarchical Linear Unconditional Model of Shared Control

The parameters related to Shared Control may be interpreted as follows (Table K.5): On average, the Shared Control score for the design class was 3.441. The *t* test result suggests that this score is different from zero (t=47.632, $p < 0.05$).

Student Level Model

Shared Control, Design = $\beta_{0j} + r_{ij}$

Team Level Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

Table K.5. Hierarchical Linear Unconditional Model for Design Class Shared Control

Fixed Effect	**Coefficient**	**SE**	**t Ratio**	**p value**
Intercept, γ_{00}	3.441	0.072	47.632	0.00
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.000	43	33.297	>0.5
Student level, r_{1j}	0.678			

Hierarchical Linear Conditional Model of Shared Control

The parameters related to Shared Control may be interpreted as follows (Table K.6): On average, the Shared Control score for the Design class was 3.423. The *t* test result suggests that this score is different from zero (t=29.550, $p < 0.05$). There is not a significant difference between Cohorts (t=-0.856, $p > 0.05$). On average, students score the Design class 0.470 points higher than their previous courses. This increase is significantly different from zero ($t = 2.029$, $p < 0.05$). There is not a significant difference between Cohorts (t=0.258, $p > 0.05$). The variance of individual scores for the Design Course is 0.003. The statistical test result suggests that scores on Shared Control do not differ significantly across students ($X^2 = 32.759$, $p > 0.05$). Due to a low level two class, the variance may be biased. The intraclass correlation is 0.0511 or 5% of variation is due to teams.

Student Level Model

Shared Control, Design = $\beta_{0j} + \beta_{1j}$*(Prior Shared Control) + r_{ij}

Team Level Model

$\beta_{0j} = \gamma_{00} + \gamma_{01}$*(Cohort) + u_{0j}

$\beta_{1j} = \gamma_{10} + u_{1j}$

Cohort was dummy coded (Cohort 2=0; Cohort 3=1). Prior Shared Control scores were team mean centered.

Table K.4. Hierarchical Linear Model of Critical Voice for the Design Class

Table K.6. Hierarchical Linear Model of Shared Control for the Design Class				
Fixed Effect	**Coefficient**	**SE**	**t Ratio**	**p value**
Intercept, γ_{00}	3.423	0.118	29.550	0.000
Cohort, γ_{01}	-0.129	0.151	-0.856	0.397
Prior, γ_{10}	0.470	0.231	2.029	0.049
Cohort on Prior, γ_{11}	0.071	0.274	0.258	0.798
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.029	32	32.759	0.430
Prior Shared Control slope, u_1	0.100	32	44.402	0.071
Student level, r_{ij}	0.538			

Hierarchical Linear Unconditional Model of Student Negotiation

The parameters related to Student Negotiation may be interpreted as follows (Table K.7): On average, the Student Negotiation score for the design class was 4.088. The *t* test result suggests that this score is different from zero (t=58.582, $p < 0.05$).

Student Level Model

Student Negotiation, Design = $\beta_{0j} + r_{ij}$

Team Level Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

Table K.7. Hierarchical Linear Unconditional Model for Design Class Shared Control

Fixed Effect	**Coefficient**	**SE**	**t Ratio**	**p value**
Intercept, γ_{00}	4.088	0.070	58.582	0.00
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.000	43	30.405	>0.5
Student level, r_{1j}	0.633			

Hierarchical Linear Conditional Model of Student Negotiation

The parameters related to Student Negotiation may be interpreted as follows (Table K.8): On average, the student negotiation score for the Design class was 3.977. The *t* test result suggests that this score is different from zero (t=32.928, $p < 0.05$). There is not a significant difference between Cohorts (t=1.187, $p > 0.05$). On average, students score the Design class 0.127 points higher than their previous courses. This increase is not significantly different from zero ($t = 0.363$, $p > 0.05$). There is not a significant difference between Cohorts for this (t=0.665, $p > 0.05$). The variance of individual scores for the Design Course is 0.000. The statistical test result suggests that scores on Student Negotiation do not differ significantly across students ($X^2 = 21.850$, $p > 0.05$). Due to a low level two class, the variance may be biased. The intraclass correlation is 0.0002 or .02% of variation is due to teams.

Student Level Model
Student Negotiation, Design = $\beta_{0j} + \beta_{1j}$*(Prior Student Negotiation) + r_{1j}

Team Level Model
$\beta_{0j} = \gamma_{00} + \gamma_{01}$*(Cohort) + u_{0j}
$\beta_{1j} = \gamma_{10} + \gamma_{11}$*(Cohort) + u_{1j}

Cohort was dummy coded (Cohort 2=0; Cohort 3=1). Prior Student Negotiation scores were team mean centered.

Table K.8. Hierarchical Linear Model of Student Negotiation for the Design Class

Fixed Effect	Coefficient	SE	t Ratio	p value
Intercept, γ_{00}	3.977	0.121	32.928	0.000
Cohort, γ_{01}	0.182	0.153	1.187	0.243
Prior, γ_{10}	0.127	0.349	0.363	0.718
Cohort on Prior, γ_{11}	0.253	0.381	0.665	0.509
Random Effect	**Variance Component**	**df**	χ^2	**p value**
Team level, u_{0j}	0.000	33	21.850	>0.500
Prior Student Negotiation slope, u_1	0.002	33	35.301	0.360
Student level, r_{ij}	0.642			

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